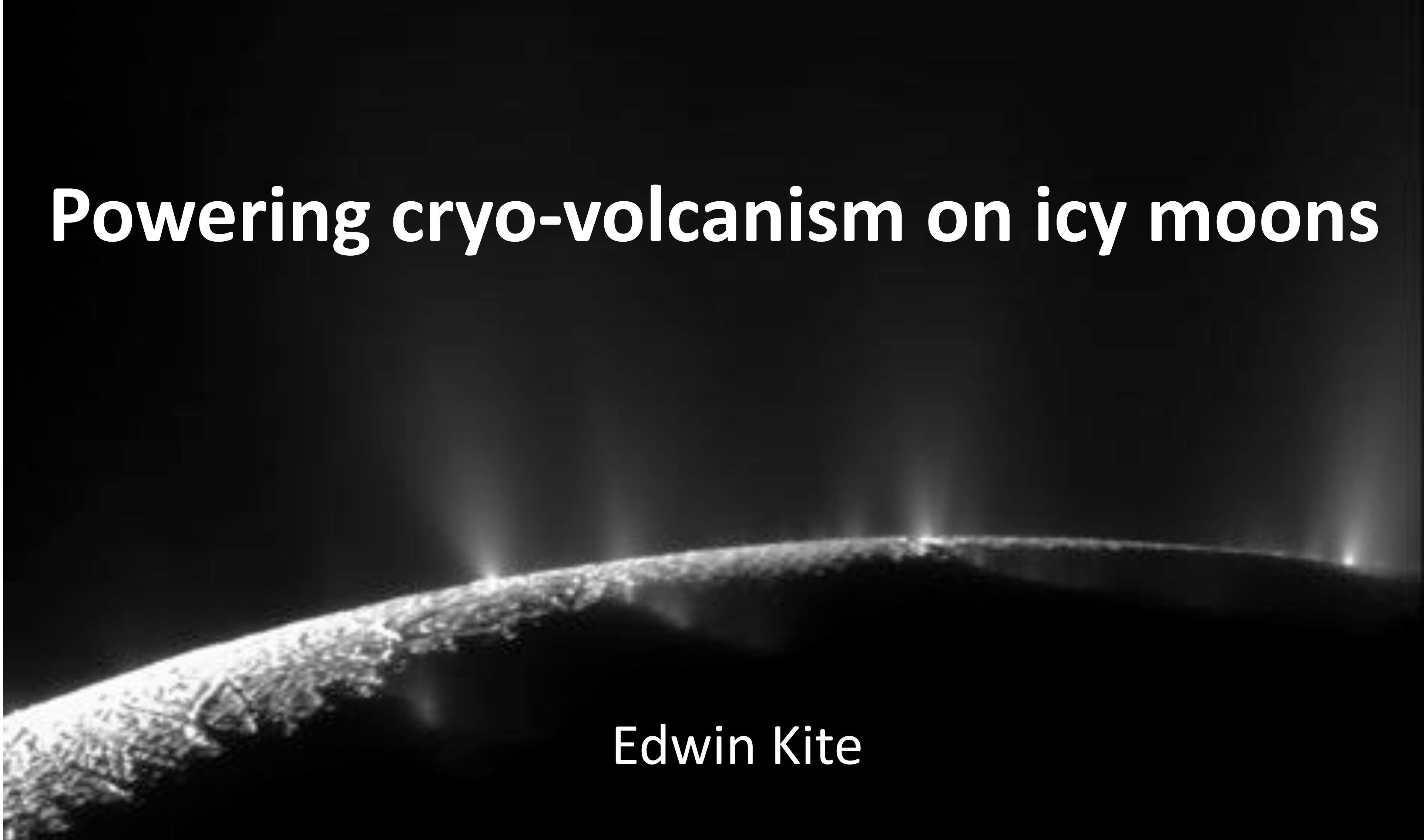
Powering cryo-volcanism on icy moons

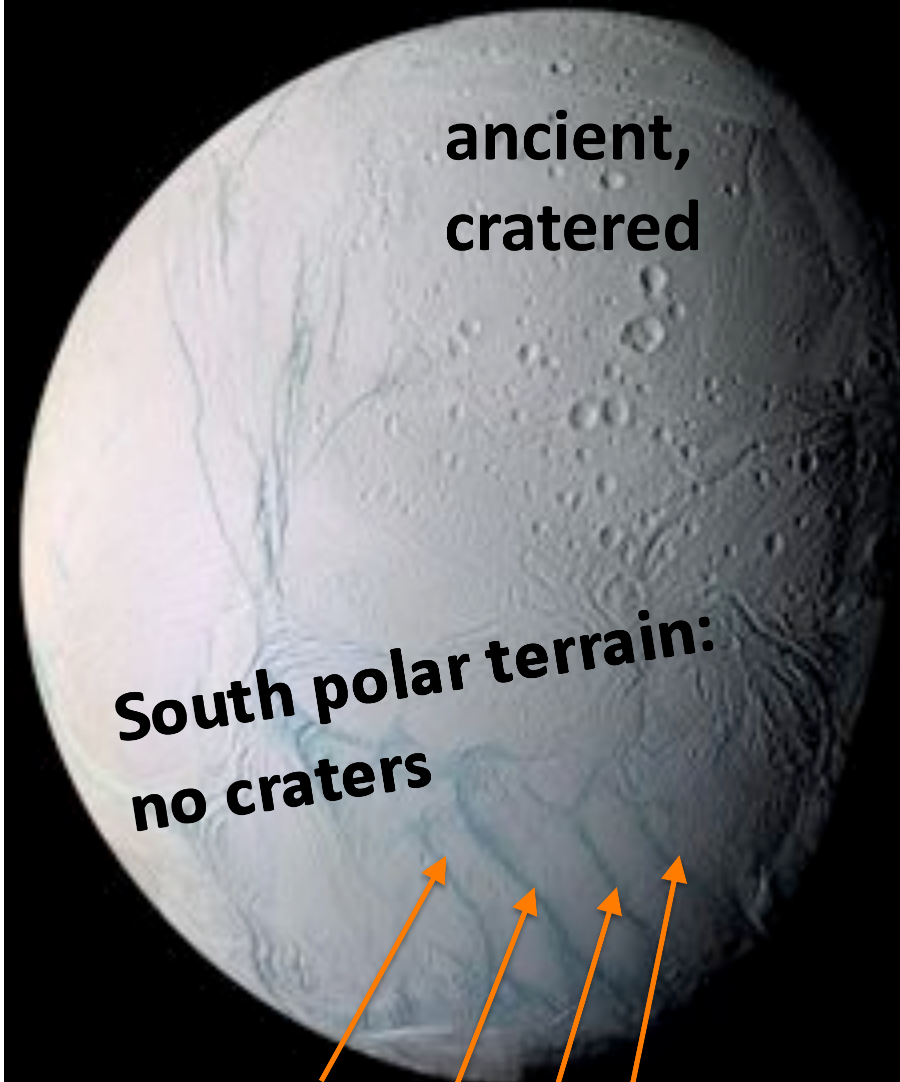


Edwin Kite

Arizona State University, 17 February 2016

~200 kg/s water ice erupting from 250 km-diameter Enceladus sustains a $>10^2$ yr old ring around Saturn.

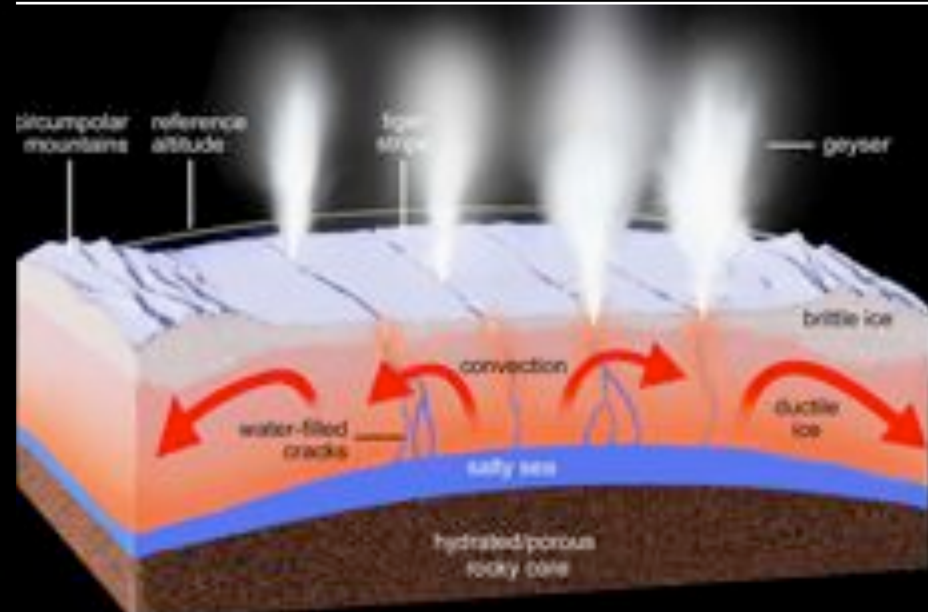
Cryo-volcanism on Enceladus has deep tectonic roots.



4 continuously-active "tiger stripes"

water source = subsurface ocean

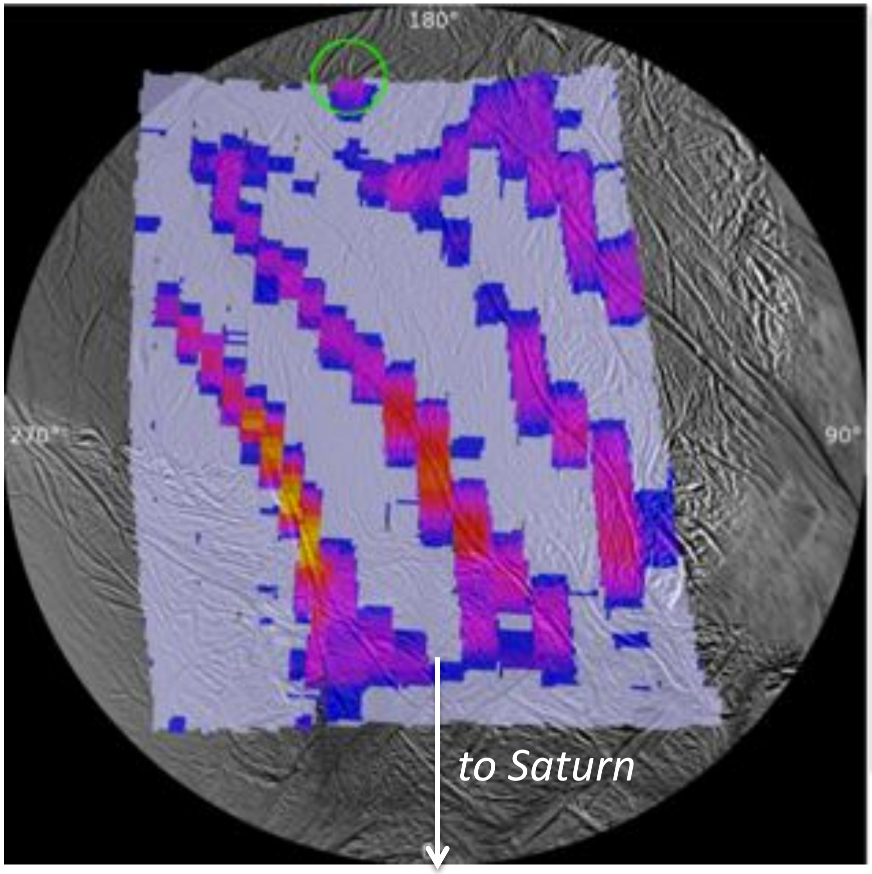
Postberg et al. 2009, 2011; Hu et al. 2015
Iess et al. 2014; Porco et al. 2014; Waite et al. 2009; Nimmo & Spencer 2013



Density of Enceladus = 1.6 g/cc

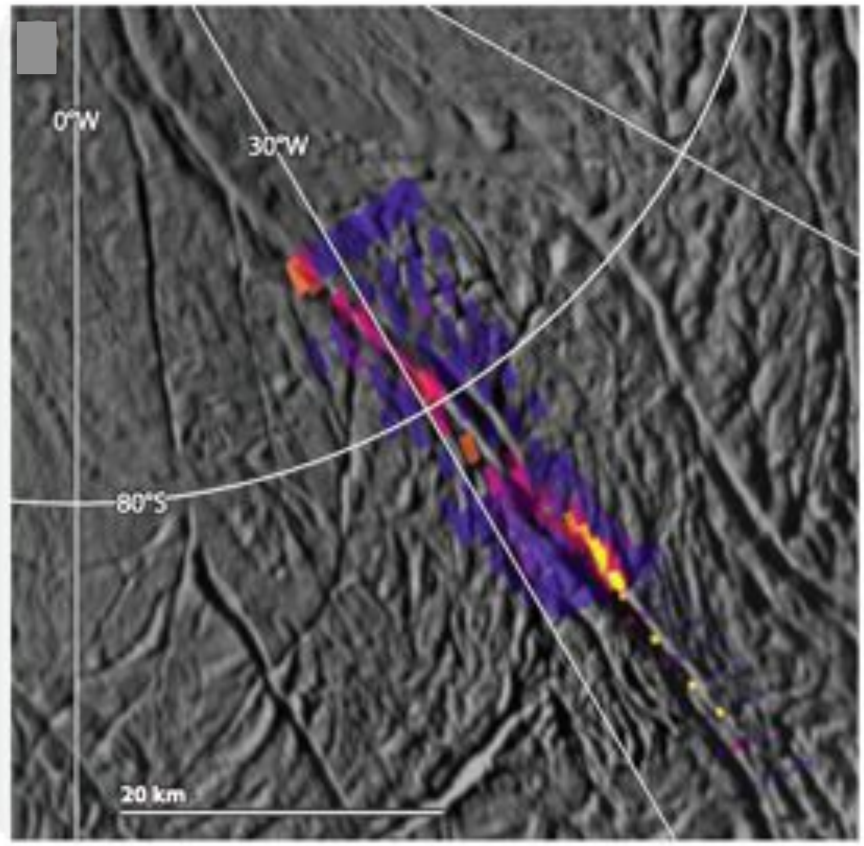
~5 GW excess thermal emission from surface fractures (100-km long "tiger stripes")

South polar view of Enceladus:
moon is tidally locked



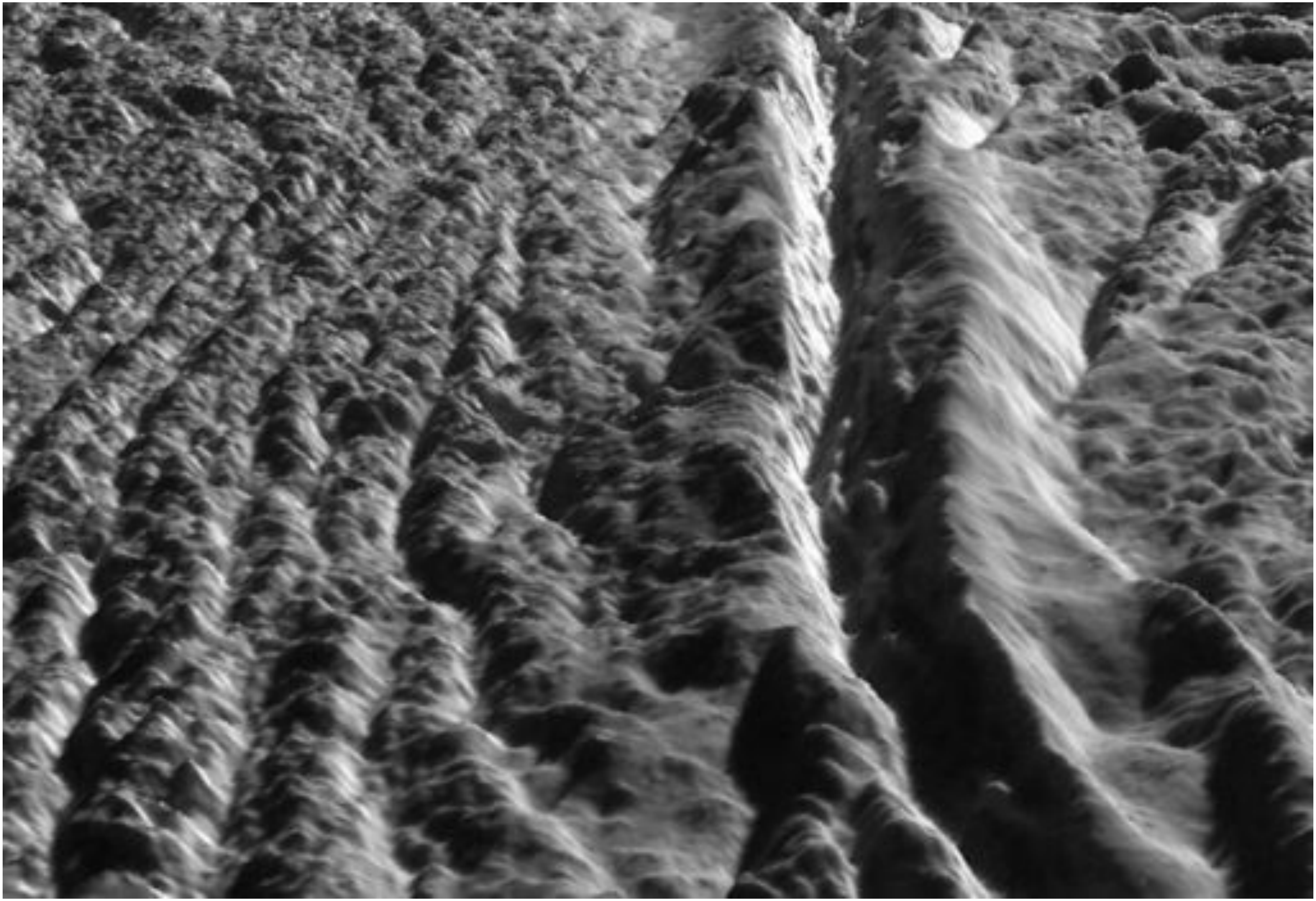
Porco et al. AJ 2014

Close-up of one "tiger stripe"



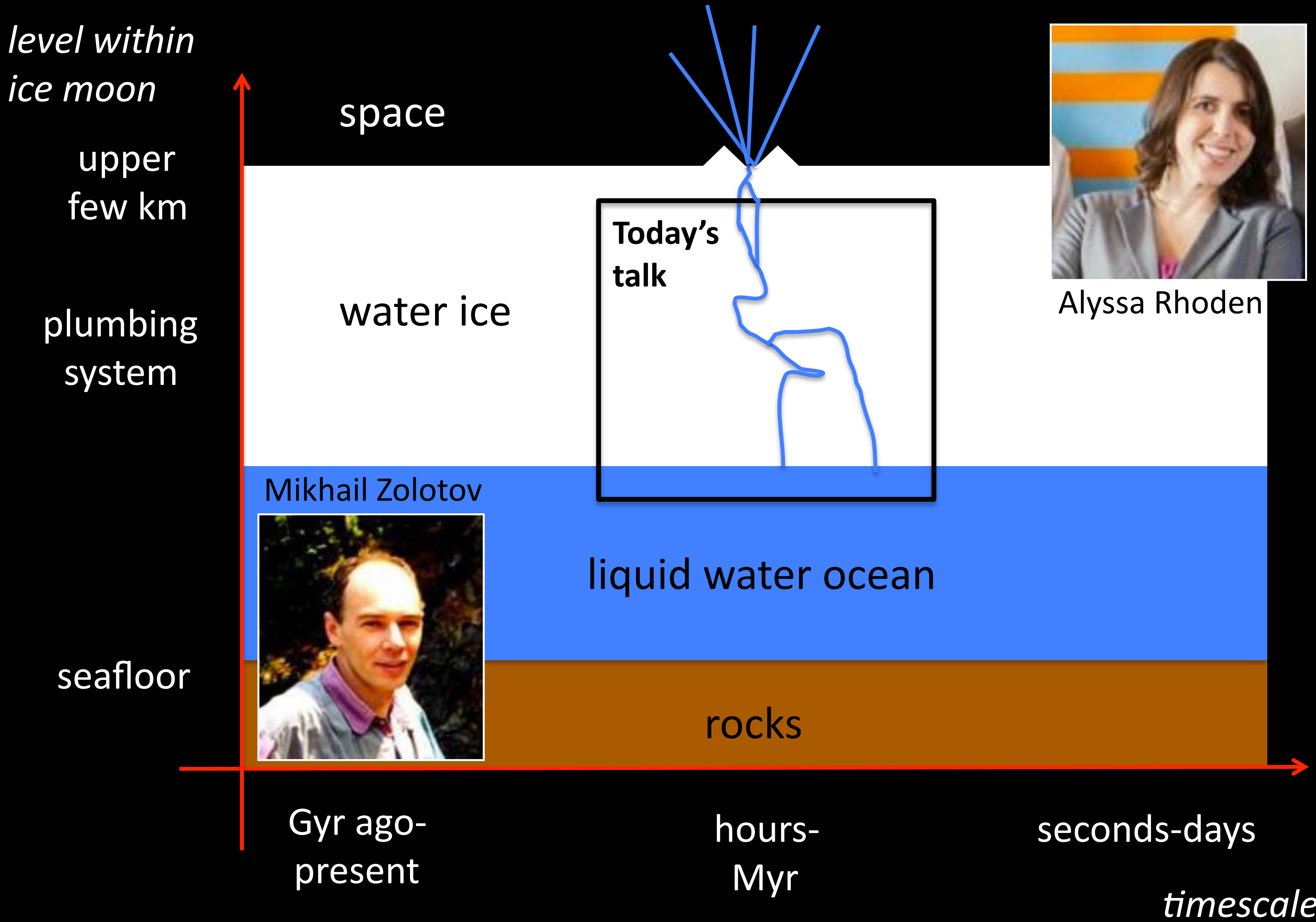
Spencer & Nimmo AREPS 2013

Hotspots up to 200K
No liquid water at surface
Latent heat represented by plumes < 1 GW



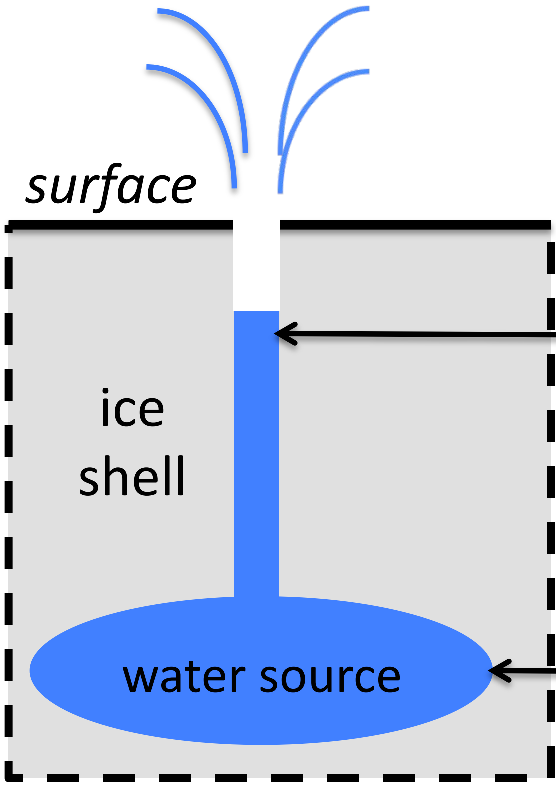
Perspective view of one of the “tiger stripes” 10x vertical exaggeration (NASA)

context for Enceladus' plumbing system



Today: How are eruptions sustained on 10^1-10^6 yr timescales?

Kite & Rubin, accepted by PNAS.



astrobiology

Tsou et al. 2012
McKay et al. 2014

Prevailing view: conduit = crack

e.g. Hurford et al. 2007, Nimmo et al. 2007, Olgin et al. 2011, Smith-Konter & Pappalardo 2008

---

habitability

Parkinson et al. 2008

Water ultimately sourced from a sub-ice ocean

e.g. Postberg et al. 2009, 2011; Hu et al. 2015; Iess et al. 2014; Porco et al. 2014; Waite et al. 2009; Nimmo & Spencer 2013; Zolotov, 2007.

Understanding the sustainability of water eruptions on Enceladus has broad implications

Tectonics:
Mass loss and vent temperature → boundary conditions for ice-shell faulting and flow

Atmospheric chemistry:
Throttles supply of oxygen to Titan's reducing atmosphere

Soils and geomorphology:
Cryo-ash builds up on small "cueball" moons of Saturn: landslides, channels

Planet formation:
Clues to anomalously variable densities of mid-sized Saturnian moons

Comparative planetology:
Is Enceladus the key to understanding Europa?

Open questions

Engine:
What powers Enceladus volcanism?

Tidal heating is the only plausible candidate, but location of heating is poorly constrained.

Source:
What is the water source for Enceladus' eruptions?

A salty ocean is connected to the surface, but exposing ocean water to space raises energy balance problems.

Plumbing system:
How can conduits between ocean and surface avoid freezing shut?
(w/Allan Rubin, Princeton U.)

Enceladus is small for active interior-driven volcanism

Only tidal heating can provide the required energy

Heat source		
Tidal	**Maximum** equilibrium (constant-eccentricity) heat production: **> 5 GW** (Fuller et al., arXiv 2016)	*Possible*
Radiogenic	**<0.32 GW** assuming CI chondritic composition	*Falls short (some also fail the "Mimas test")*
Chemical	**Water-rock reaction: <0.1 GW** (assuming complete water-rock reaction; 2.4 x 10^5 J/kg srp)	
Secular cooling	**Steady release of accretional heat <0.1 GW** ^{26}Al heating may be significant early on	
Joule heating	**<0.05 GW** (Hand et al. JGR 2011)	
Recent impact	Improbable	

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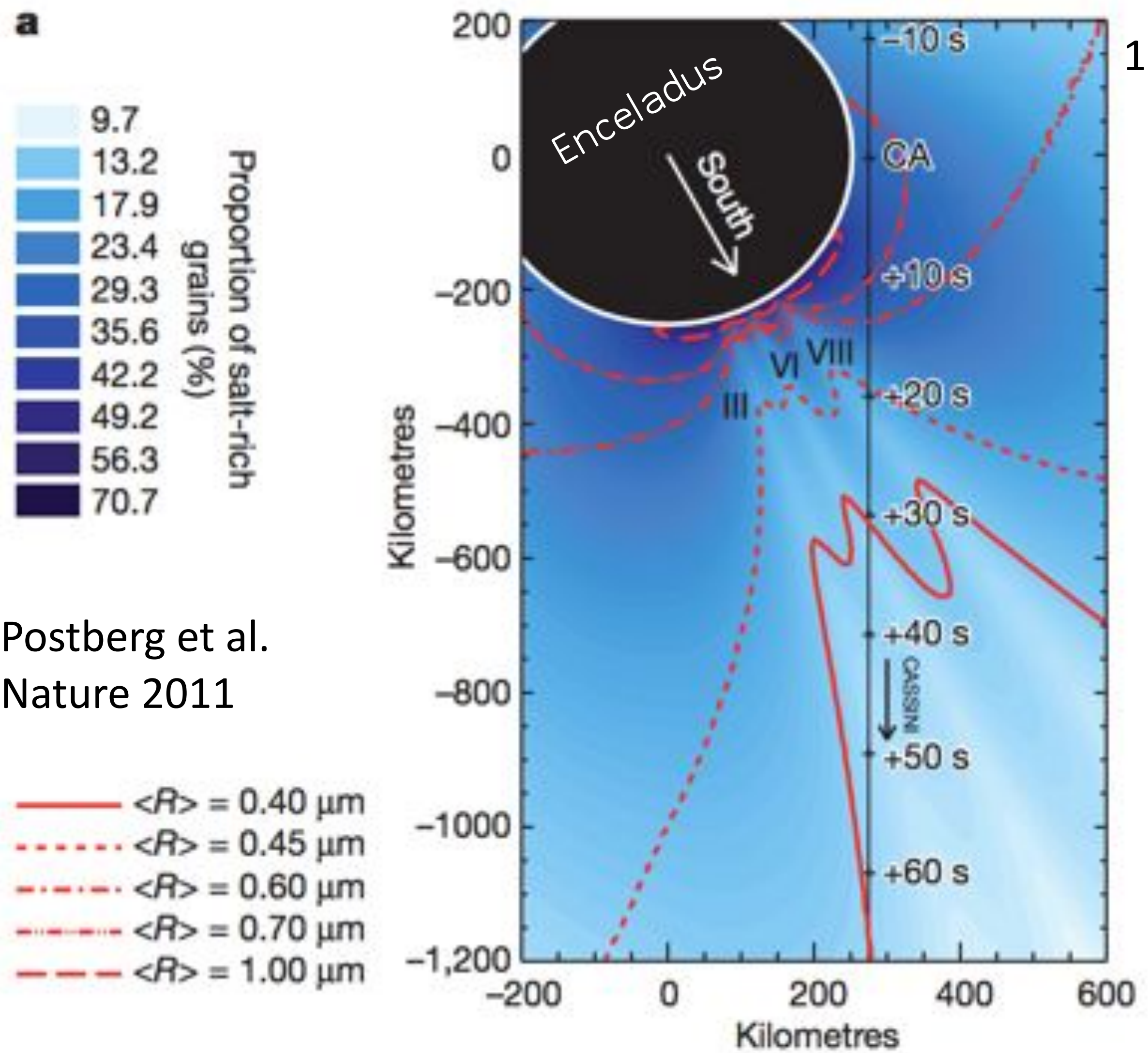
Sodium and nano-silica tell us that the source is a subsurface ocean, not clathrates or sublimation

Ocean water is exposed to space, raising energy balance problems

Plumbing system:
How can conduits between ocean and surface avoid freezing shut? (w/ Allan Rubin)

Turbulent dissipation within tiger stripes can sustain the phase curve of Enceladus' eruptions.

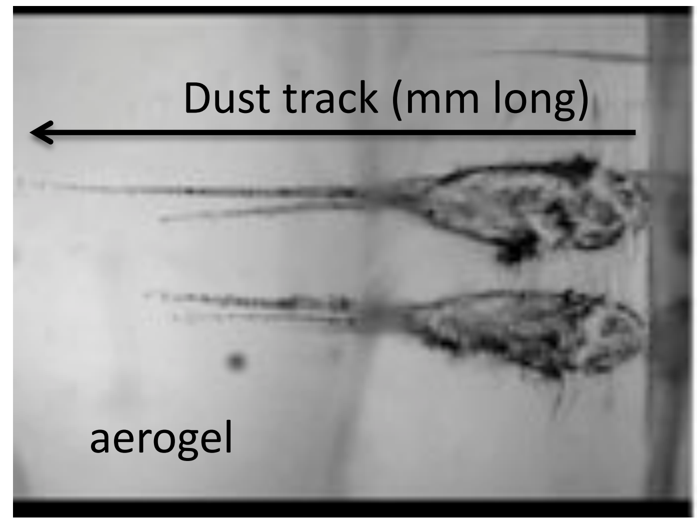
Salty particles in plume indicate ocean material is escaping to space
Nano-silica in plume hints at hydrothermal vents (active?!)



Postberg et al.
Nature 2011

18 km/s (Cassini @Enceladus)

6 km/s (Stardust mission)



Postberg et al. Nature 2011
Hsu et al. Nature 2015

Open questions

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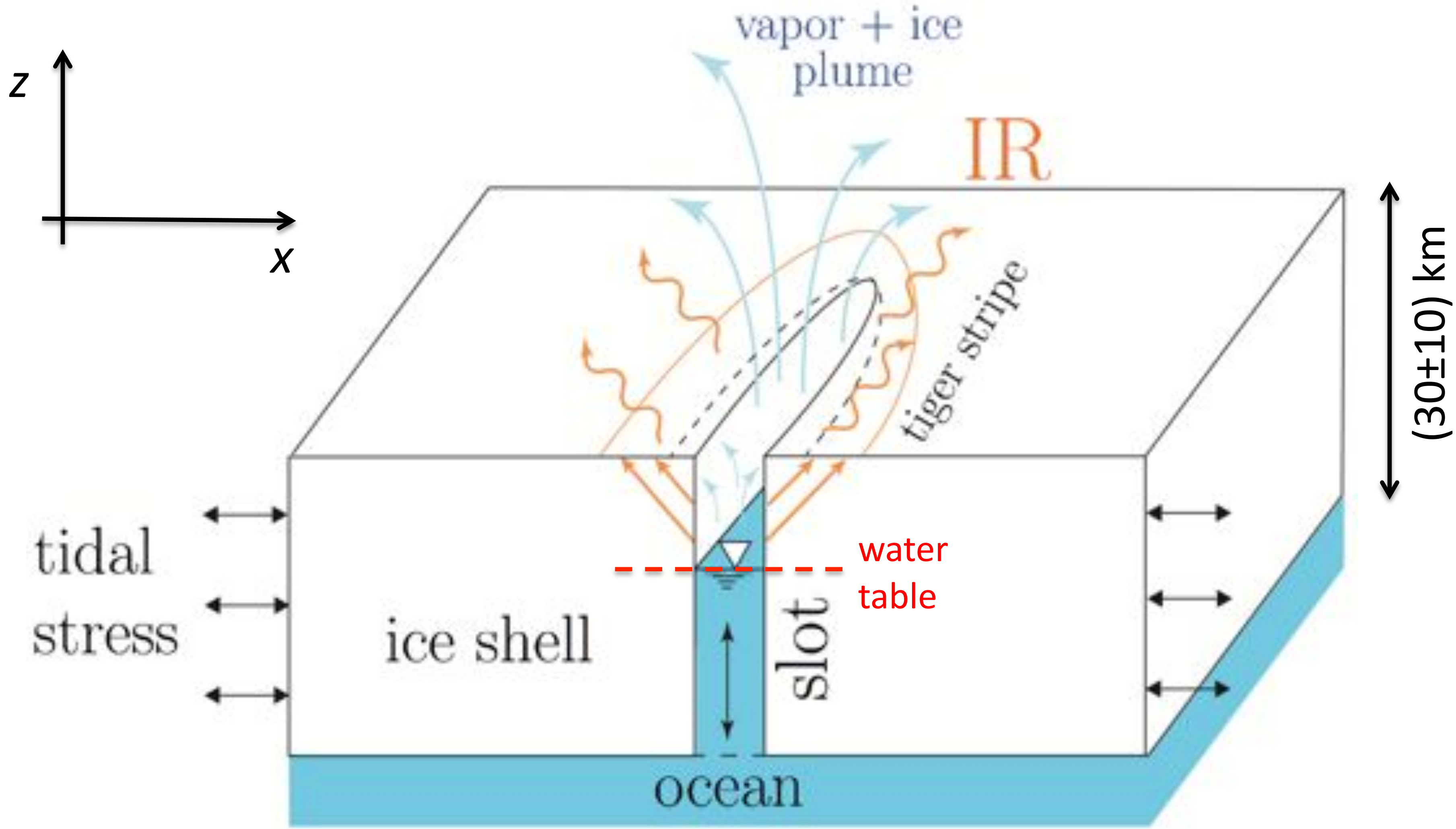
Turbulent dissipation within tiger stripes can sustain the phase curve of Enceladus' eruptions.

Key constraint: energy balance at water table



Open questions

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What powers Enceladus volcanism?

Tidal heating is the only plaus
candidate – very likely interm

Allan Rubin

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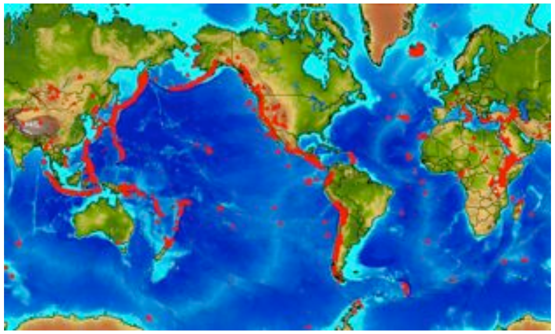
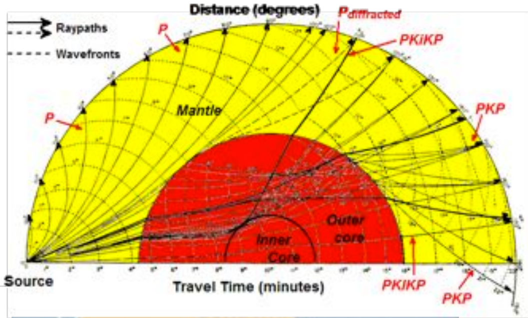
Probing tectonics

Earth

Volcanism



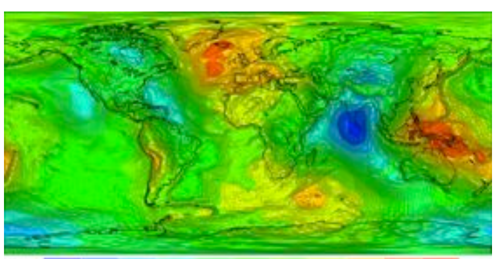
Seismicity



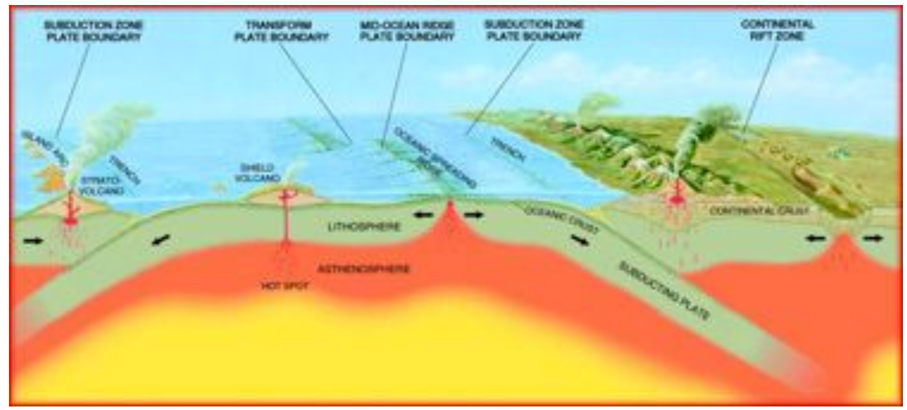
Geology

Gondwanaland reconstruction c.400 million years ago

Gravity



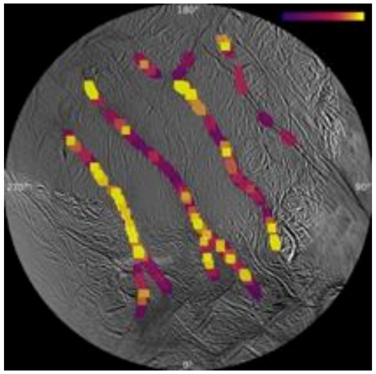
Tectonic mode:



Probing tectonics

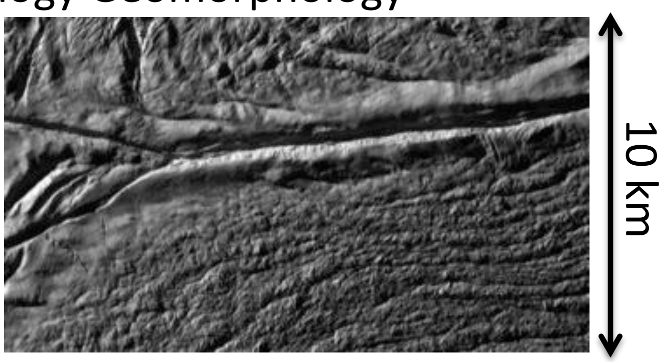
Enceladus

Volcanism

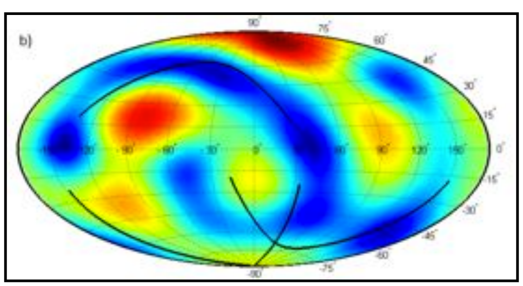


Seismicity

~~Geology~~ Geomorphology



Gravity

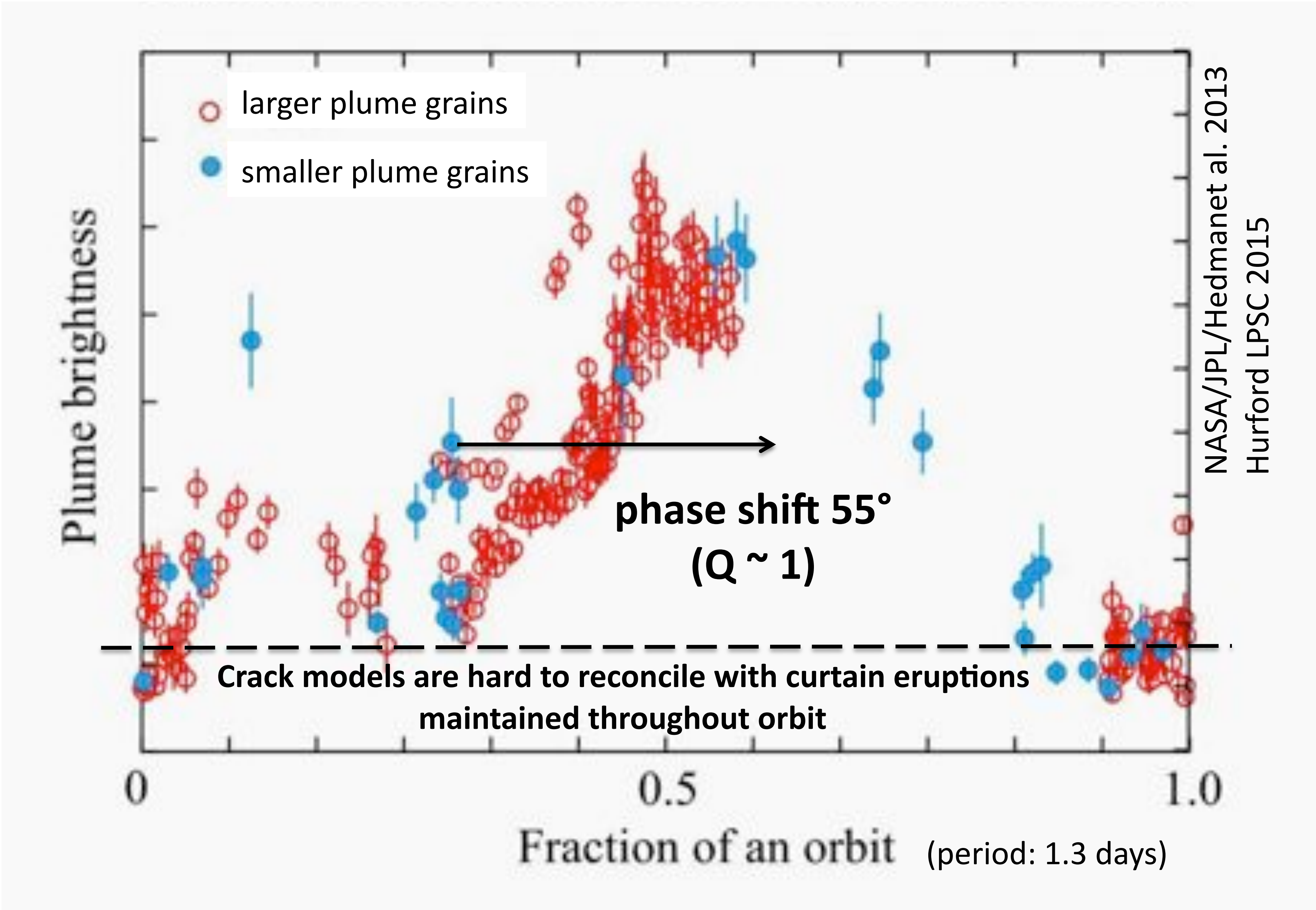


Tectonic mode:

?

Challenge for the prevailing view: Understanding tidal modulation of eruptions

(all four tiger stripes erupt as "curtains" throughout orbit; Spitale et al. Nature 2015)



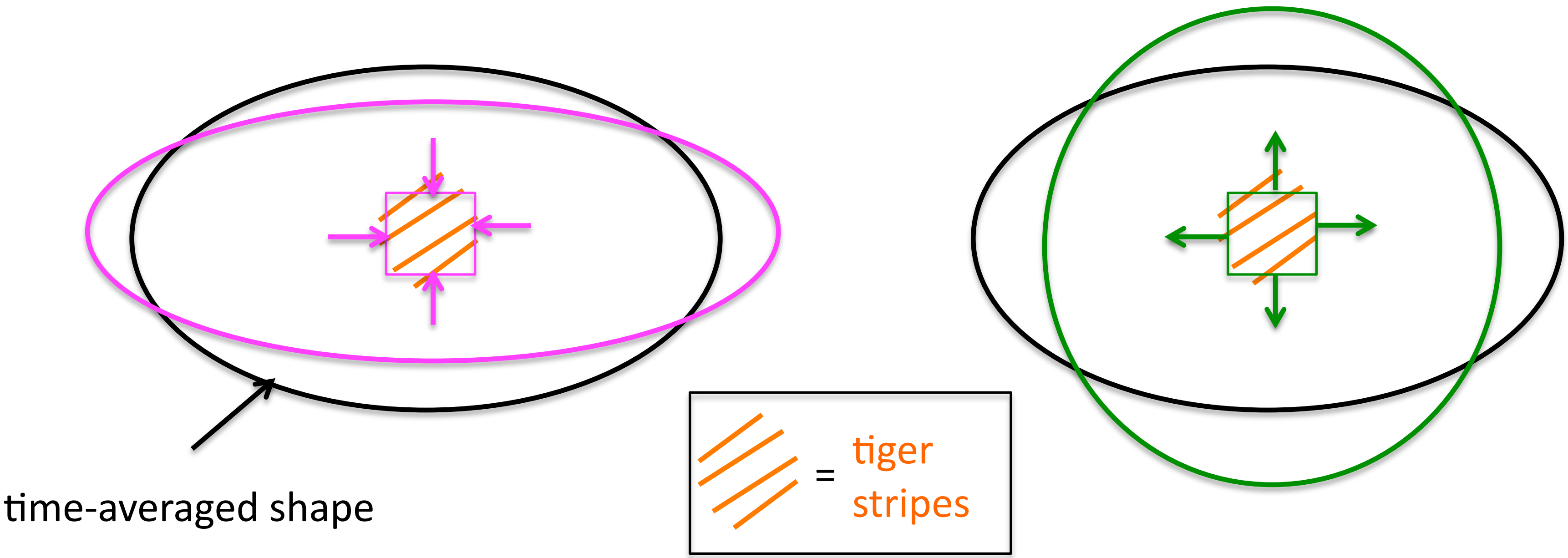
How to find tidal stresses at volcanic vents

Enceladus period = 1.3 days

Enceladus orbital ellipticity = 0.0047

Closest distance to Saturn
Looking “up” at South Pole

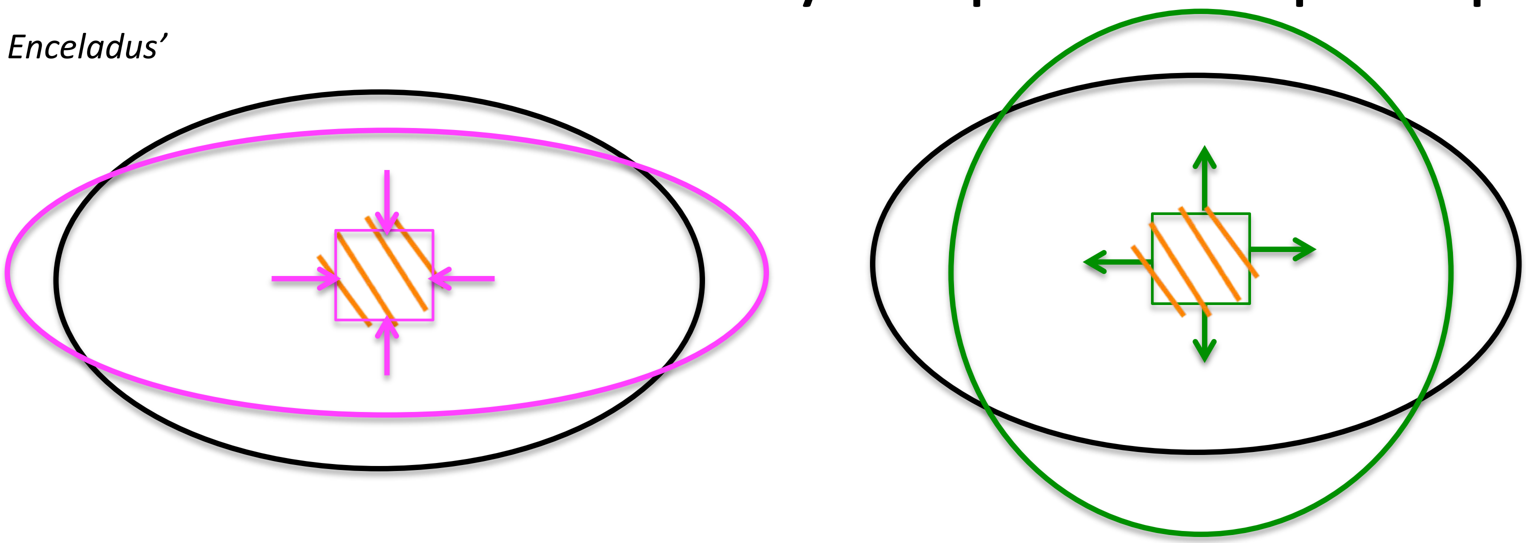
Furthest distance from Saturn
Looking “up” at South Pole

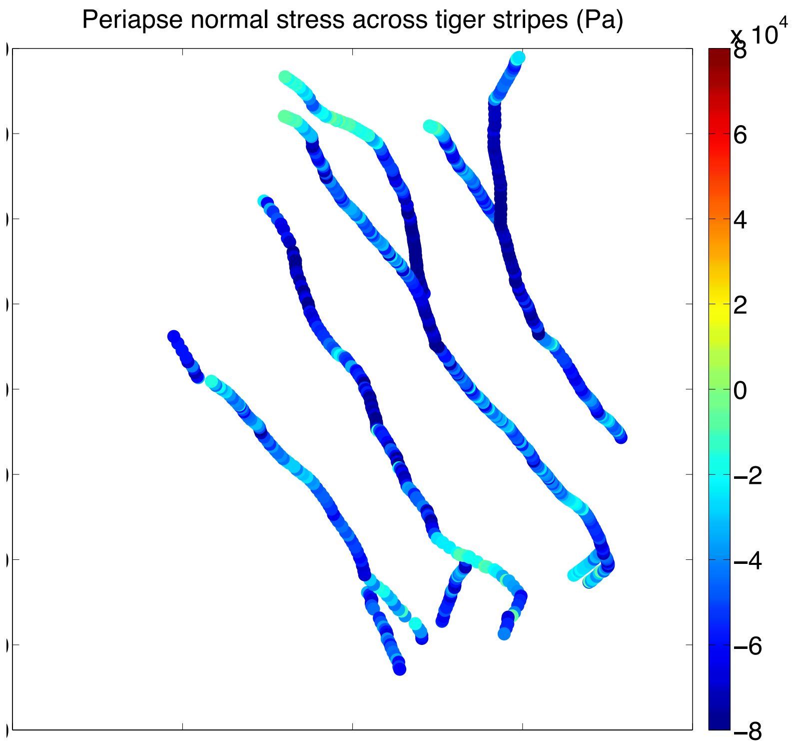


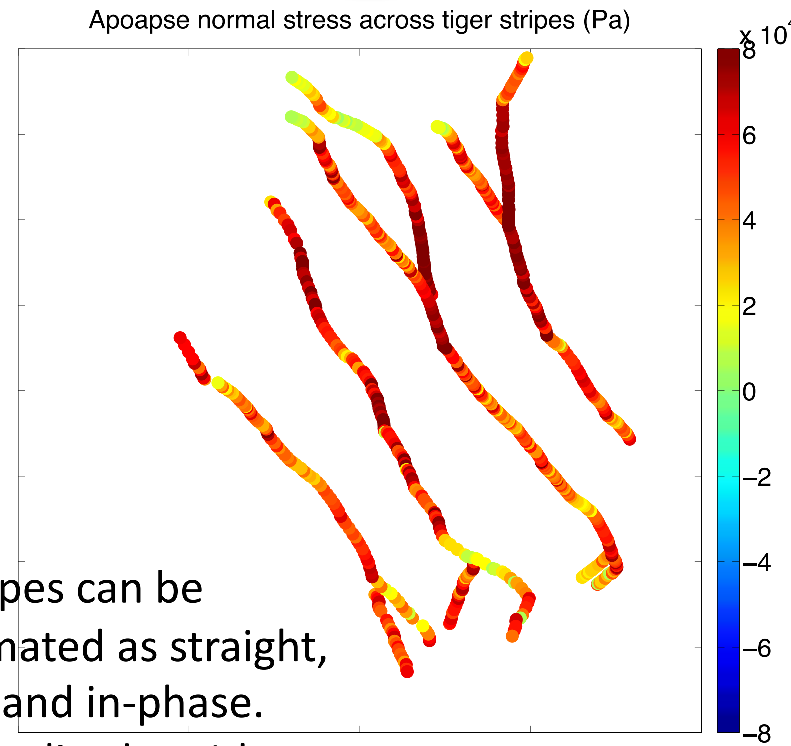
eccentricity tide only
thin-shell approximation
k_2 appropriate
for global ocean

Crack models are falsified by eruptions at periapse

looking "up" at Enceladus' south pole:



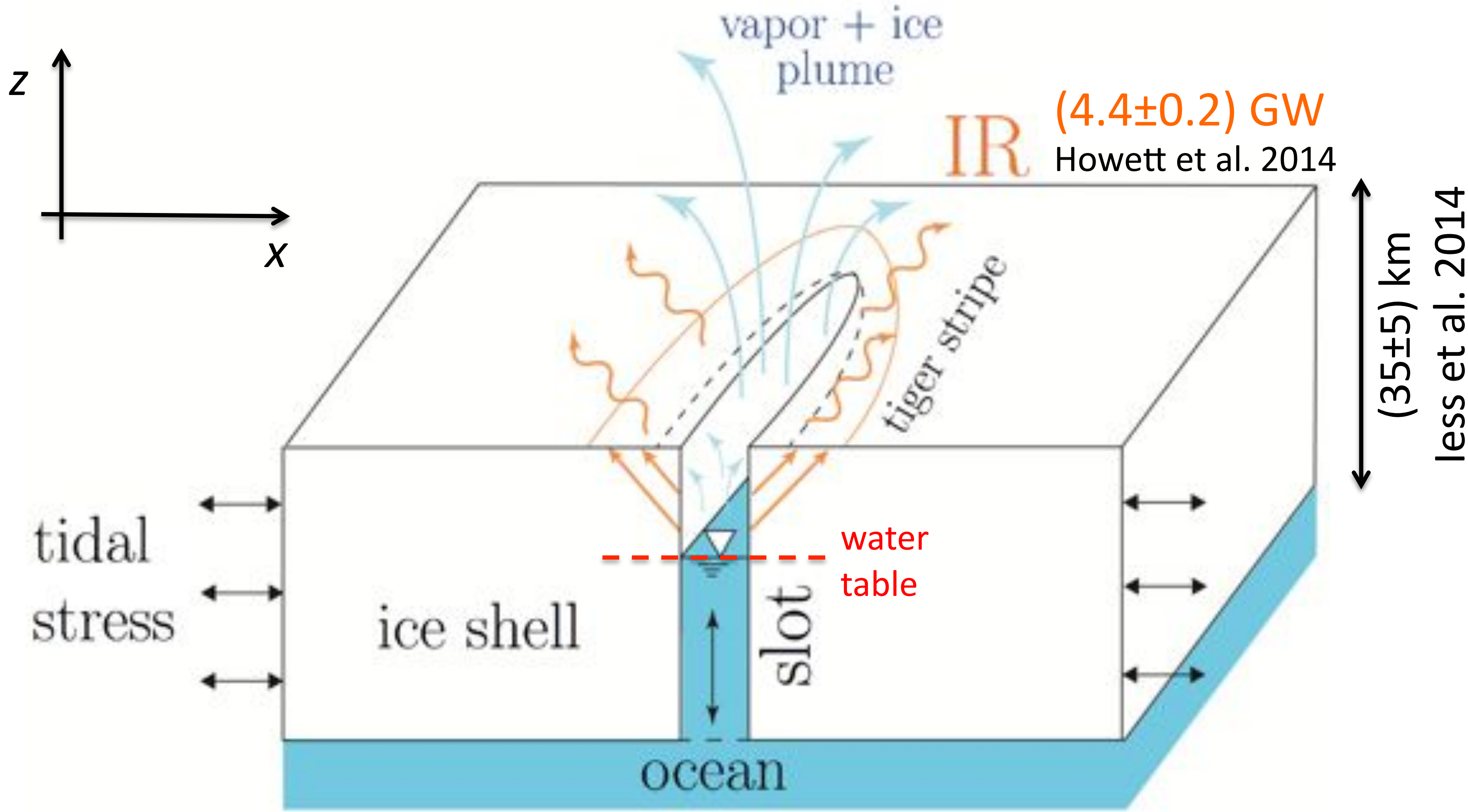




tiger stripes can be approximated as straight, parallel, and in-phase.
stress amplitude ~ 1 bar

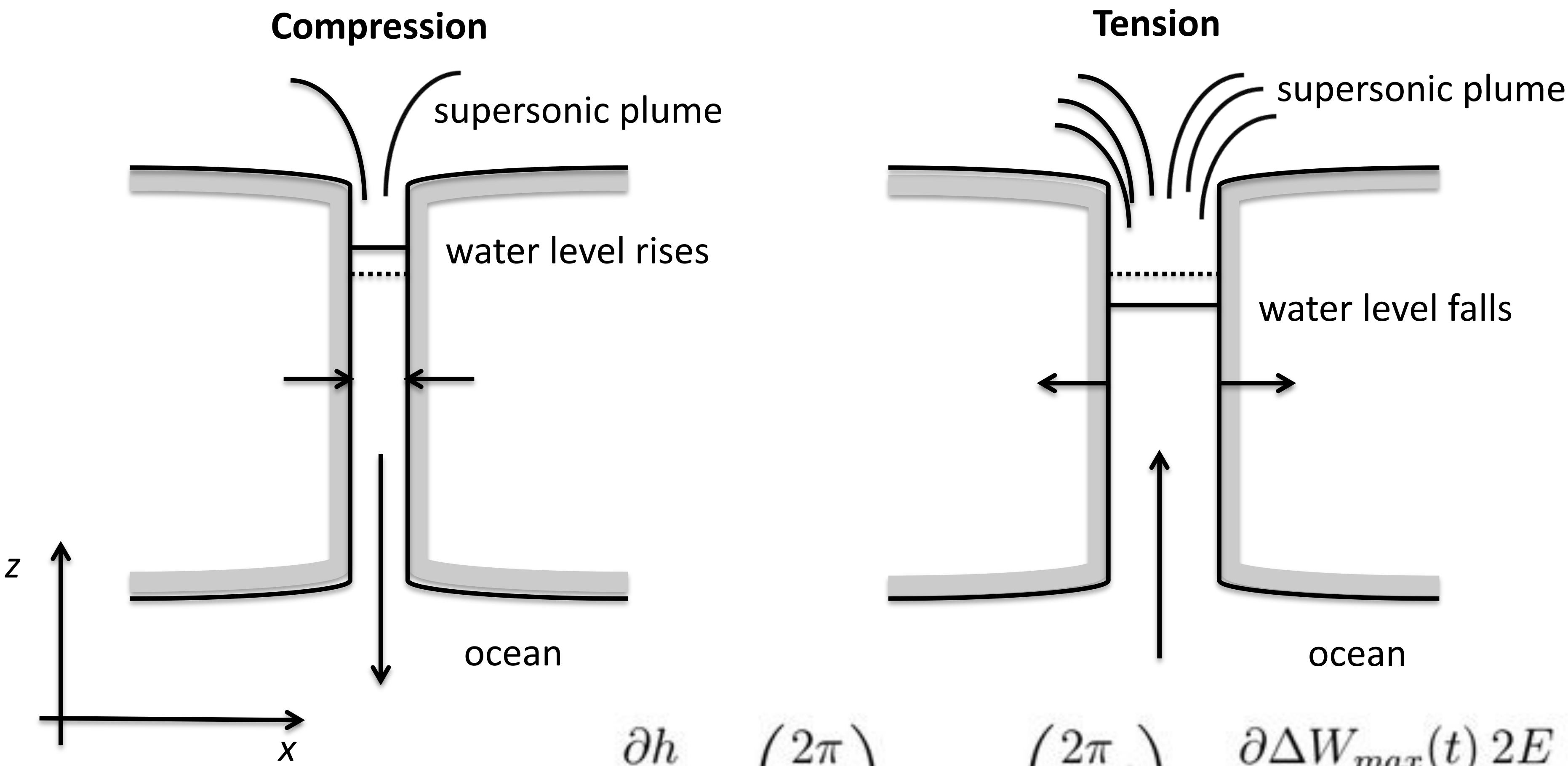
Challenge for the prevailing view: energy balance at water table

Kite & Rubin, accepted by PNAS



Alternative: Melted-back slot

Kite & Rubin, accepted by PNAS.



$$\rho_w g \frac{\partial h}{\partial t} = \left(\frac{2\pi}{p}\right)\sigma_n \cos\left(\frac{2\pi}{p}t\right) - \frac{\partial \Delta W_{max}(t)}{\partial t}\frac{2E}{L_{ts}}$$

$$\nabla P = (D+h)^{-1}(\sigma_n(t) - 2W_{max}(t)E/L_{ts})$$

Attractive properties:

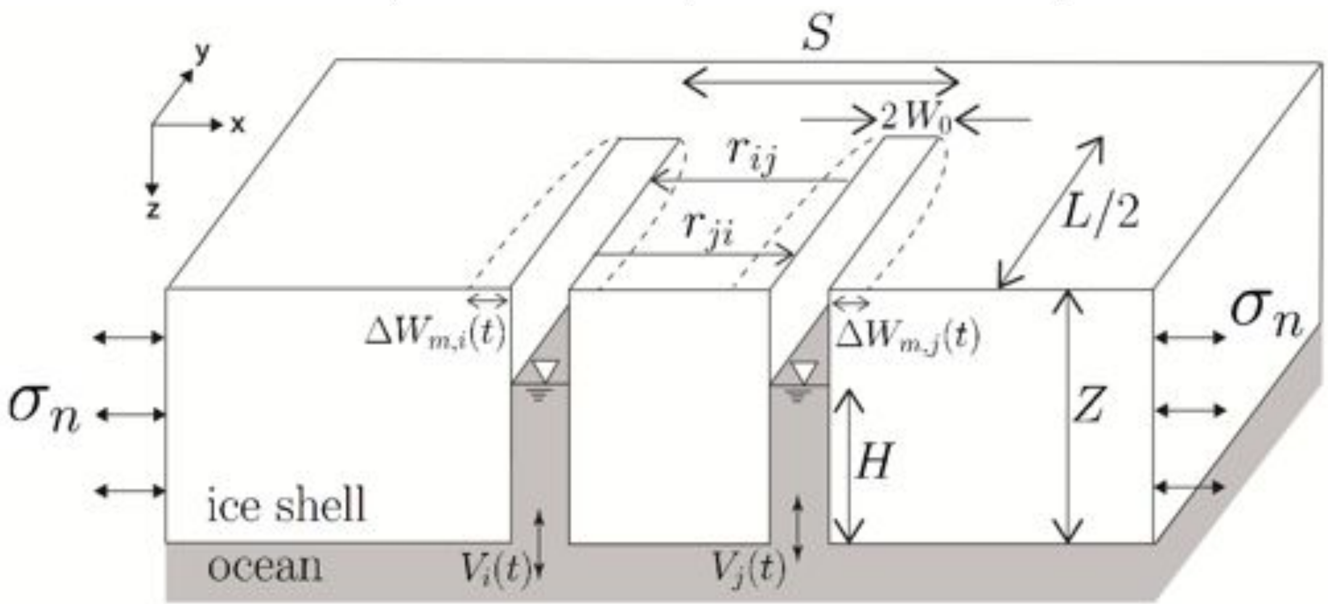
- Slot width lags tidal cycle
- Slot does not close
- Turbulent dissipation heats slot
- Pumping disrupts ice formation

Daily tidal cycle of water in tiger stripes

Kite & Rubin, accepted by PNAS.

- Change in slot width
- Width change due to water flow from ocean into slot
- Width change due to tides from Saturn
- Width change due to back-force from ice shell elasticity
- Slots interact elastically: use boundary-element method

$$\frac{\partial \Delta W_{m,i}}{\partial t} = \frac{4g\rho_w Q + 4n_f L W_{0,i}(A/2)\cos(n_f t) + \pi n_f L(r_{ii}\Delta W_{m,i} - r_{ij}\Delta W_{m,j})(A/2)\cos(n_f t)}{16EW_{0,i} + 8\pi E\Delta W_{m,i} - \pi L(A/2)\sin(n_f t) + 2\pi\rho_w g D L}$$



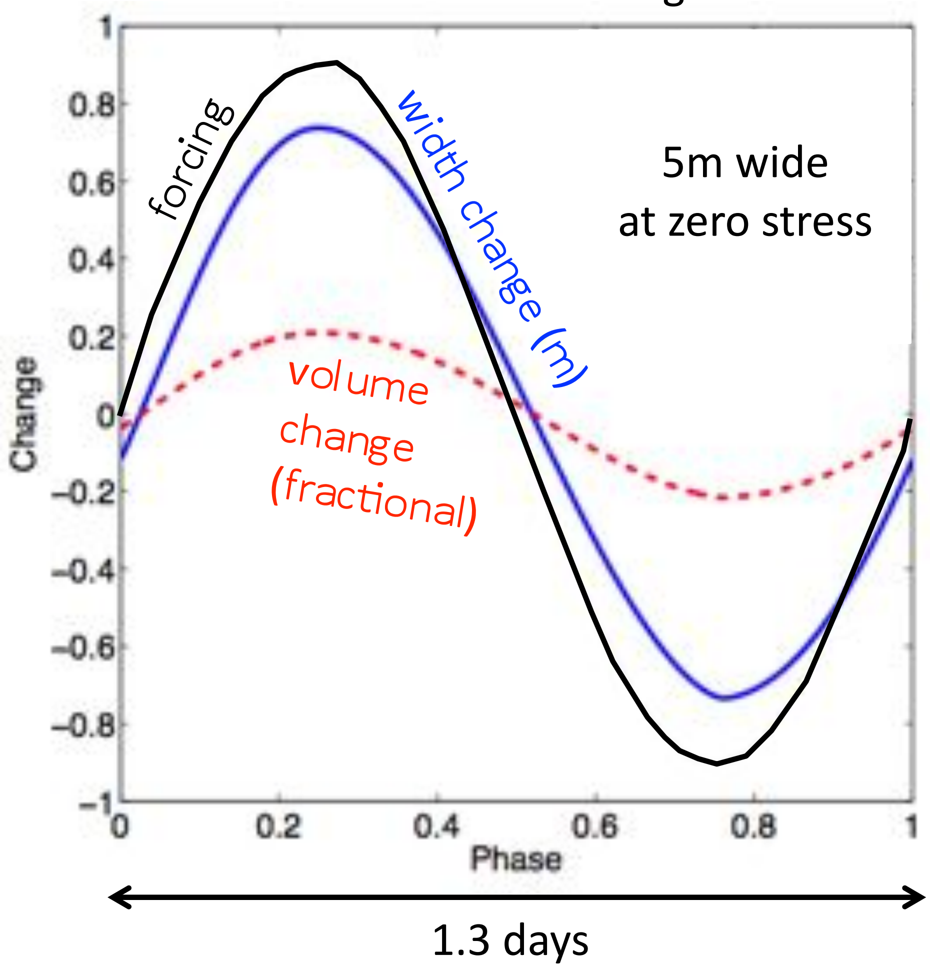
Tiger stripes can be approximated as straight, parallel and in-phase

Daily cycle of tidal flow of water in slots

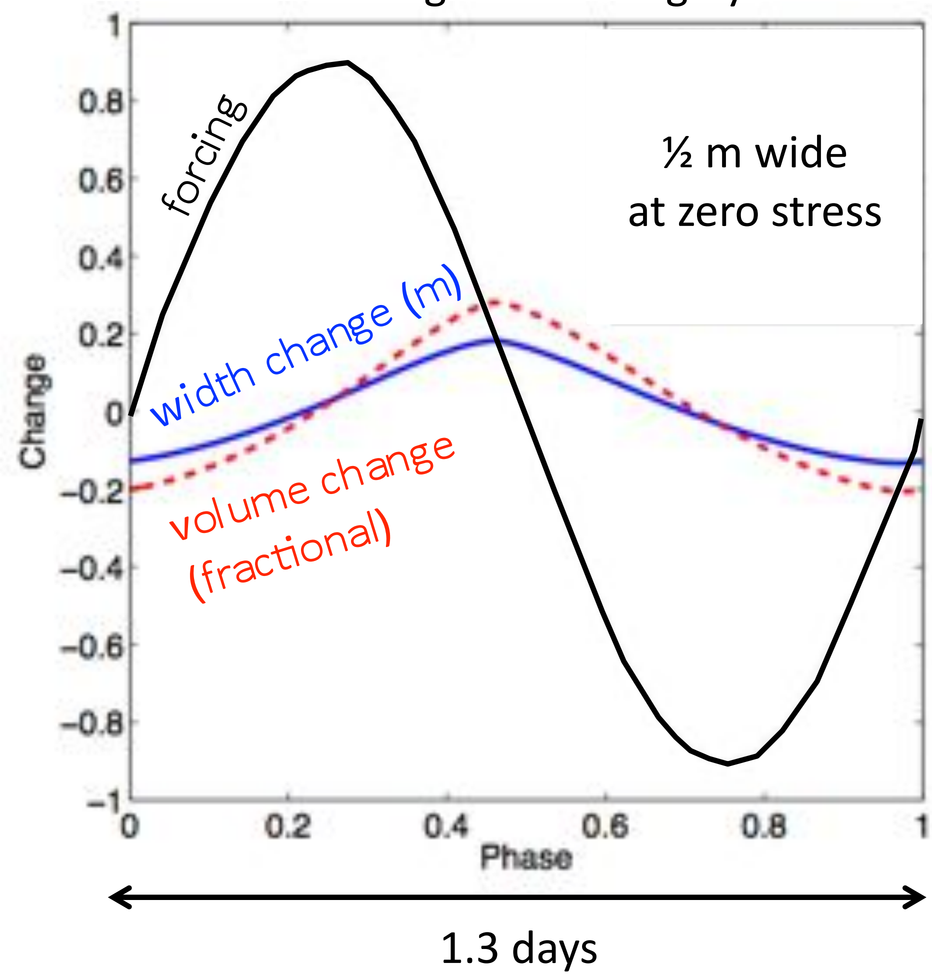
Kite & Rubin, accepted by PNAS.

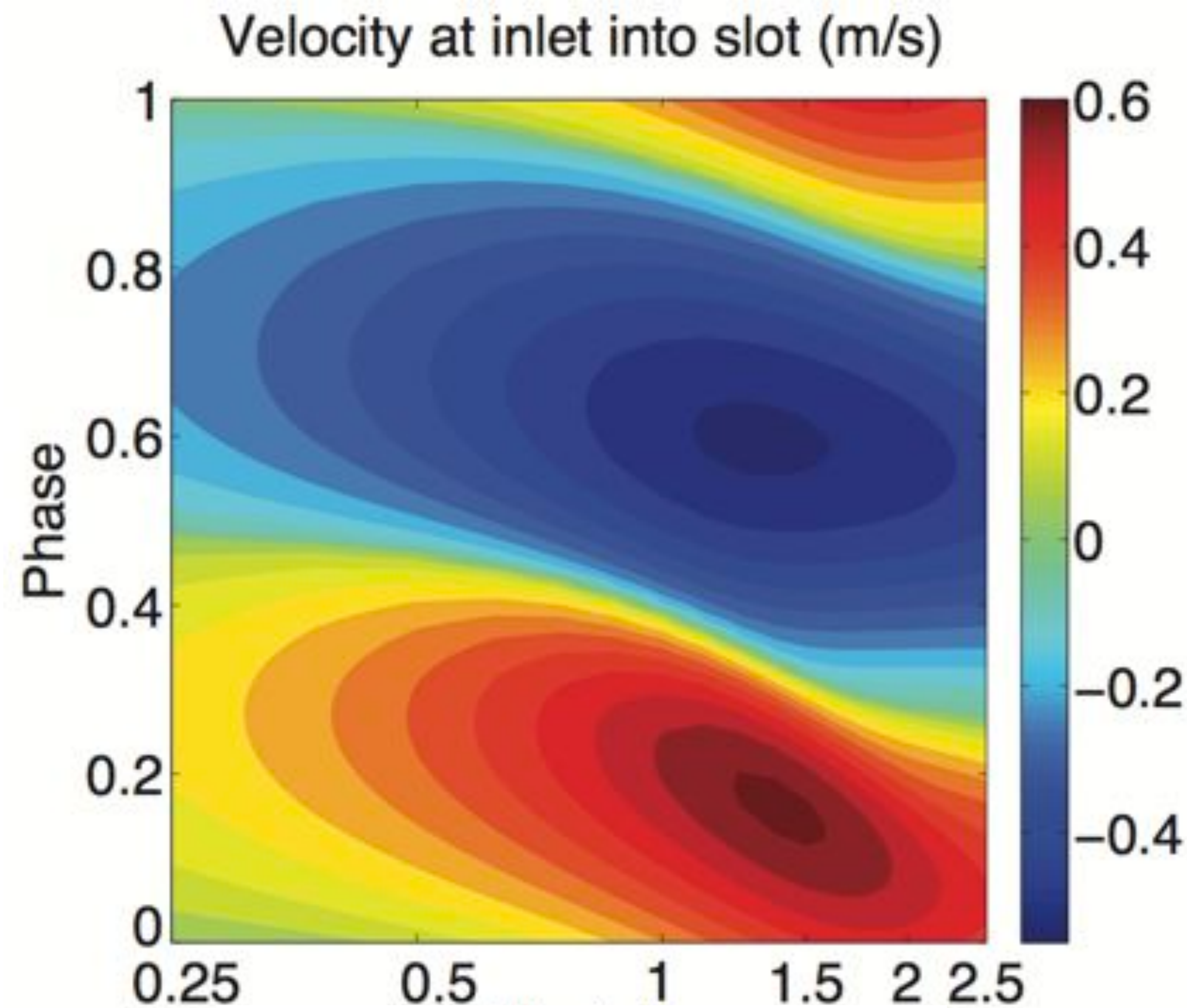
Slot width is a free parameter:

Wide slots track tidal forcing



Narrow slots lag tidal forcing by 8 hours

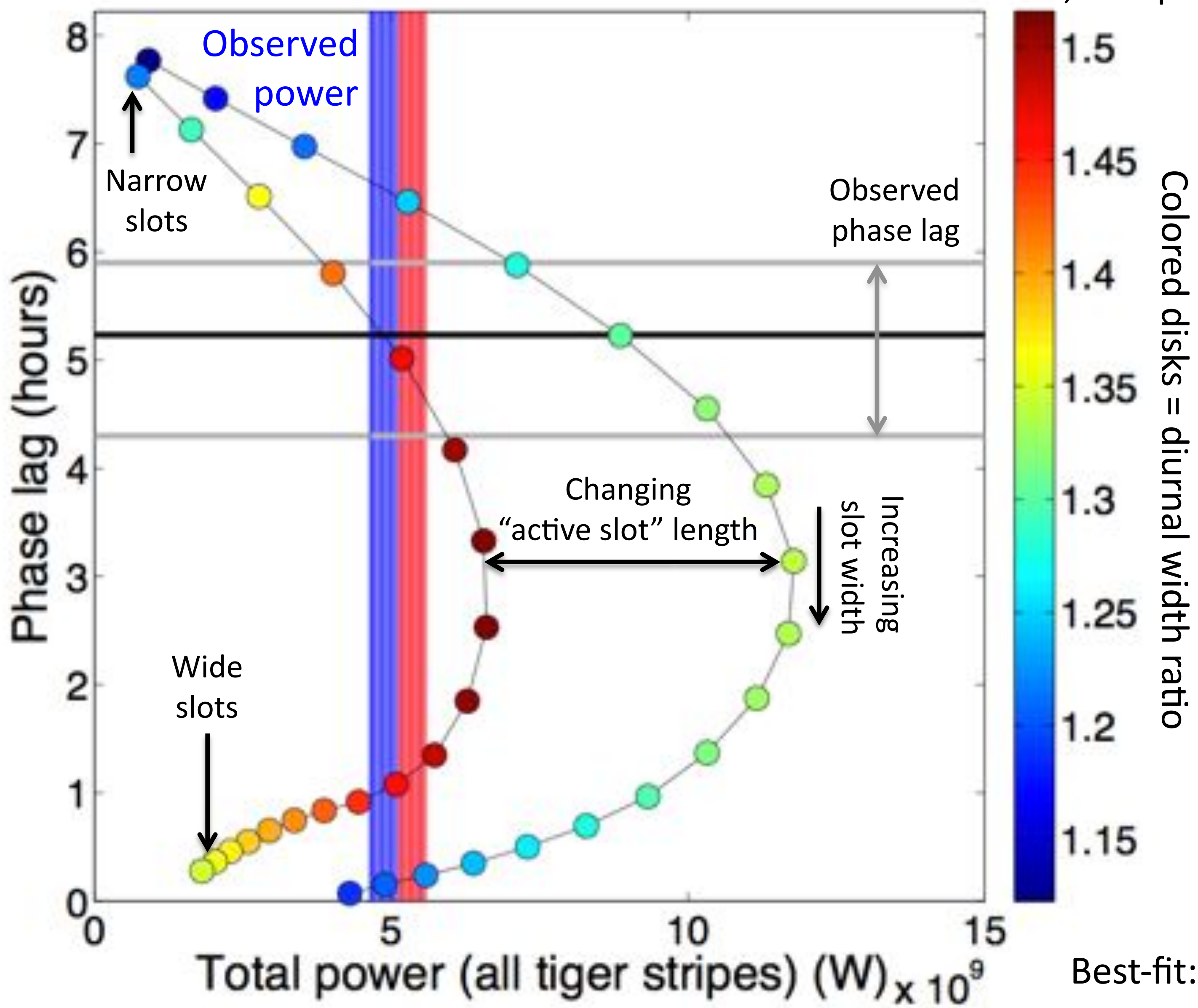




Zero-stress slot half-width (m)

Turbulent dissipation of tidally-pumped vertical flow inside tiger stripes explains power output, phase lag and sustainability of the eruptions

Kite & Rubin, accepted by PNAS.



Best-fit: 1-2 m wide

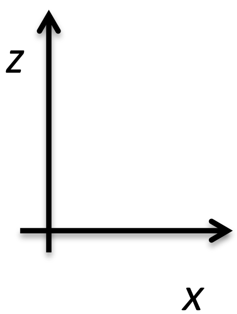

Photo: F. Kibbe

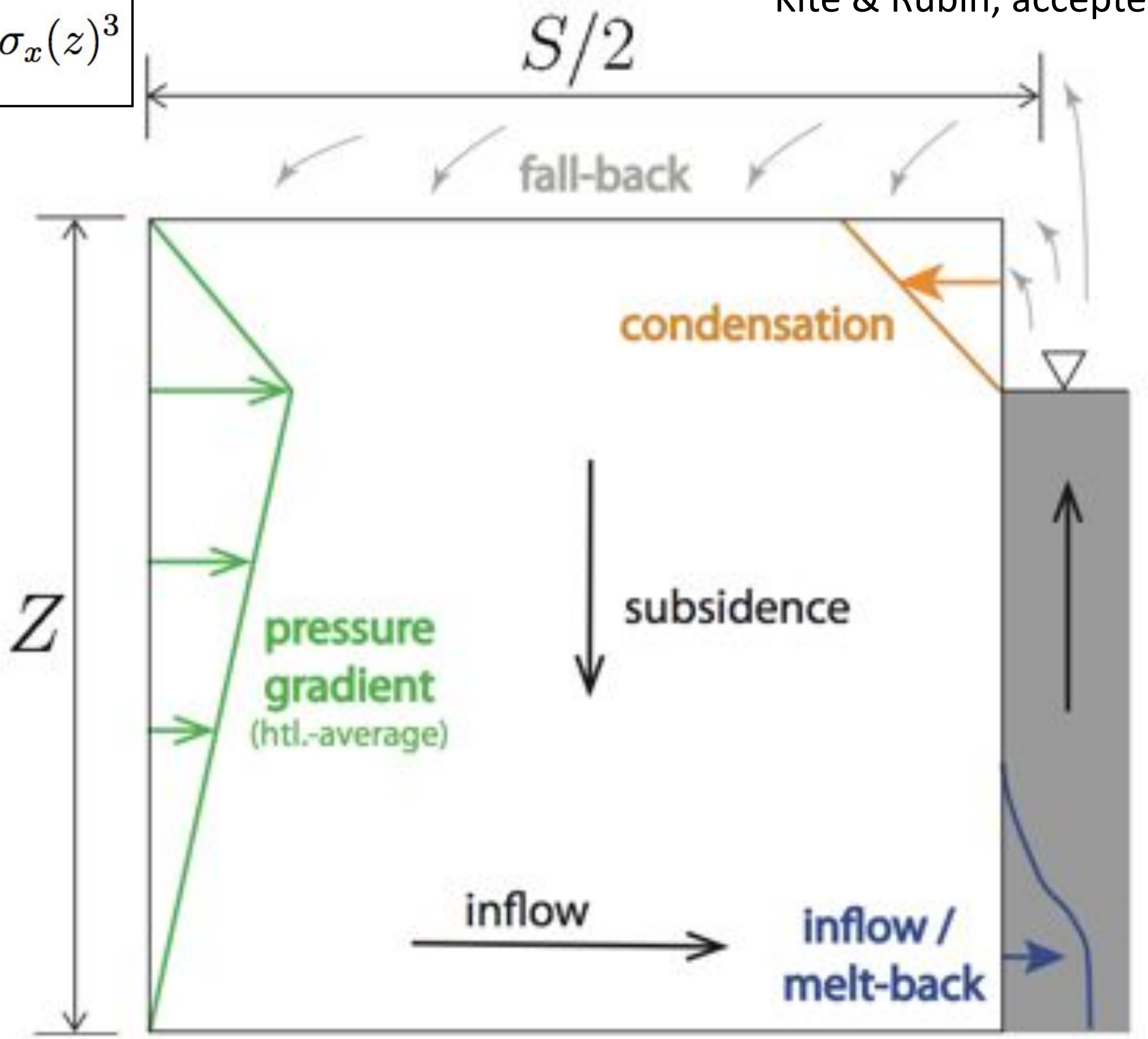
Long-lived water-filled slots have tectonic consequences

$$\dot{\epsilon}_{xx}(z) = \frac{1}{8}N(T)\sigma_x(z)^3$$

Kite & Rubin, accepted by PNAS.

COLD, STRONG ICE

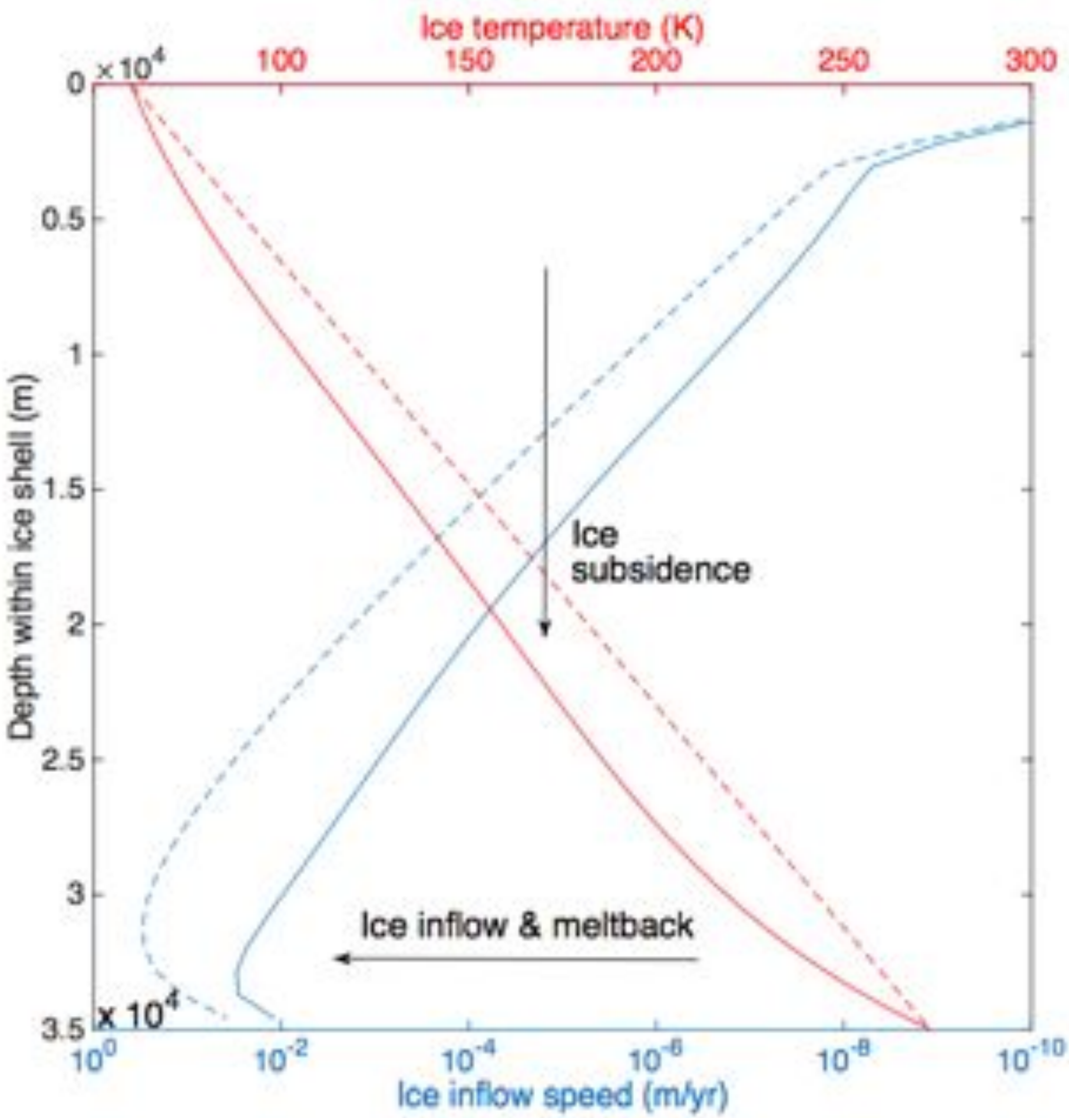




WARM, WEAK ICE

Tectonic feedback between subsidence and meltback buffers South Polar terrain power to 3-9 GW

Kite & Rubin, accepted by PNAS



Initial temperature profile (conductive)

Steady-state temperature profile (Subsidence-perturbed)

Initial ice inflow rate

Steady-state ice inflow rate

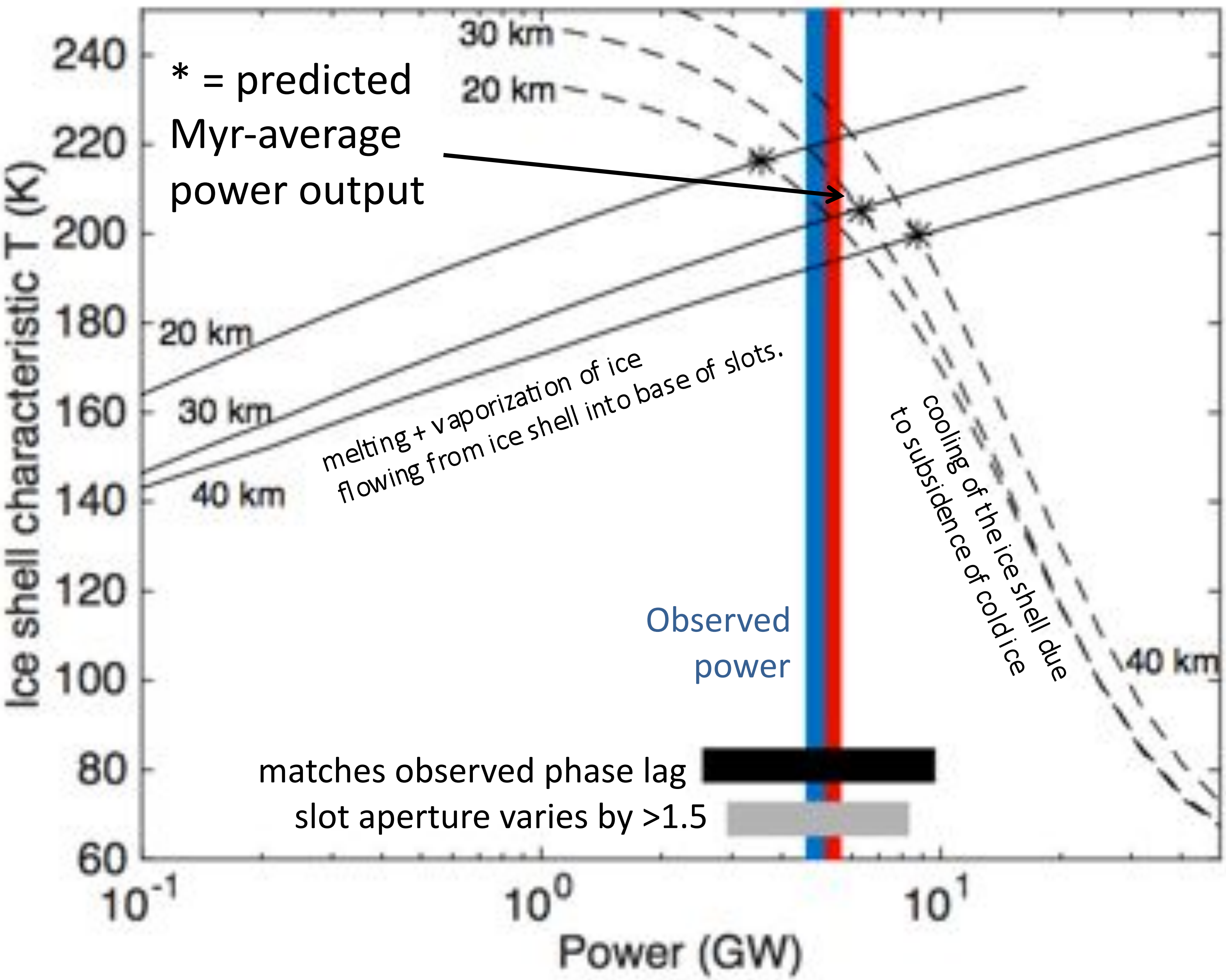
Highly simplified ice flow: assuming

$$\dot{\epsilon}_{xx}(z) = \frac{1}{8}N(T)\sigma_x(z)^3$$

Self-consistent 2D thermal structure

Summary: Slot model explains and links sustainability of volcanism on 10 yr - 10^6 yr timescales

Kite & Rubin, accepted by PNAS



Gravity indicates ice shell is 20-40 km thick (e.g., Iess et al. 2014)

Limitations and caveats

- Initiation of ocean-to-surface conduits on ice moons remains hard to explain (e.g. Crawford & Stevenson 1988).
  - may be related to ice-shell disruption at high orbital eccentricity: such disruption could have created partially-water-filled conduits with a wide variety of apertures, and evaporative losses caused by tiger stripe activity would ensure that only the most dissipative conduits (width 1-2m) endure to the present day.
- Slot stability is less of a concern.
  - along-slot stirring is rapid relative to freeze-shut and flow-shut.

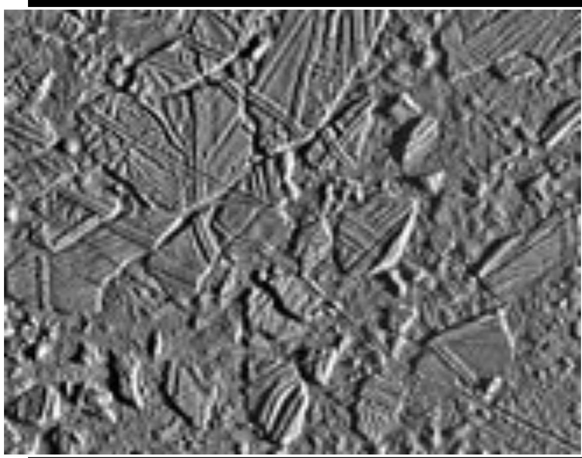
Testable predictions

Kite & Rubin, accepted by PNAS.

For the data from Cassini's final flybys:

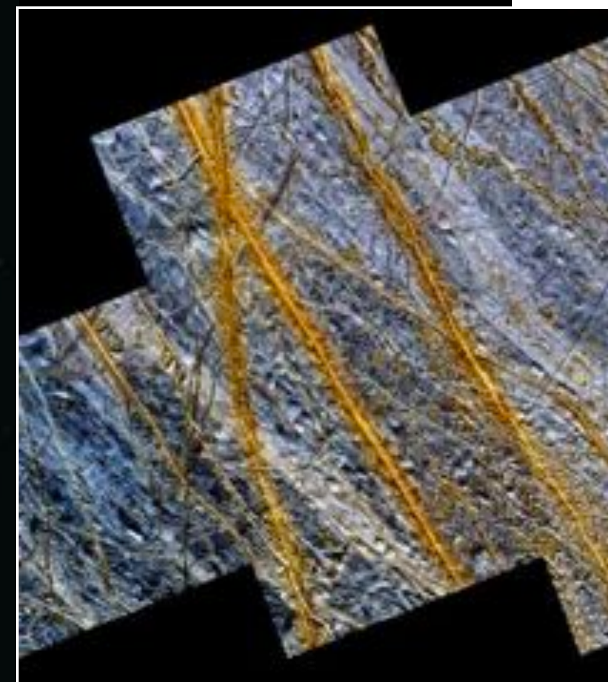
1. Endogenic thermal emission should be absent between tiger stripes.
2. No correlation between emission and *local* tiger-stripe orientation
3. Smooth distribution of thermal emission
4. Steady pattern of spatial variability, in contrast to bursty hypotheses. Vapor flux should covary with ice-grain flux.

Next step: is Enceladus the key to understanding Europa?



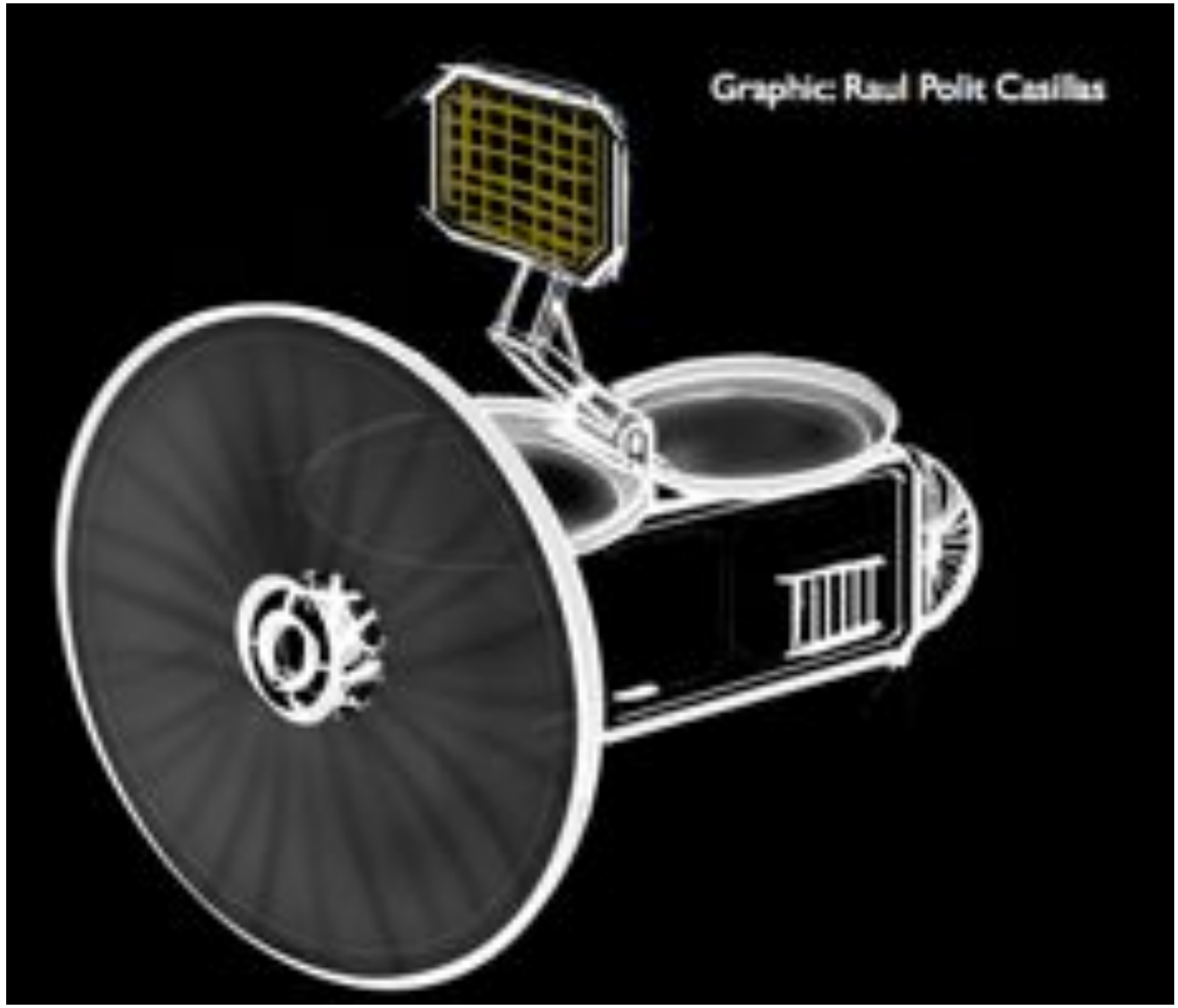
Chaos terrain

Present-day activity?
(Roth et al. Science 2014)



Colorful “double ridges”

The best* astrobiology experiment in the Solar System: Sampling ocean material at Enceladus



* terms and conditions apply.

Summary

Engine:
What powers Enceladus volcanism?

Tidal heating is the only plausible candidate

Tidal heating is the only plausible candidate, but location of heating is poorly constrained.

Source:
What is the water source for Enceladus' eruptions?

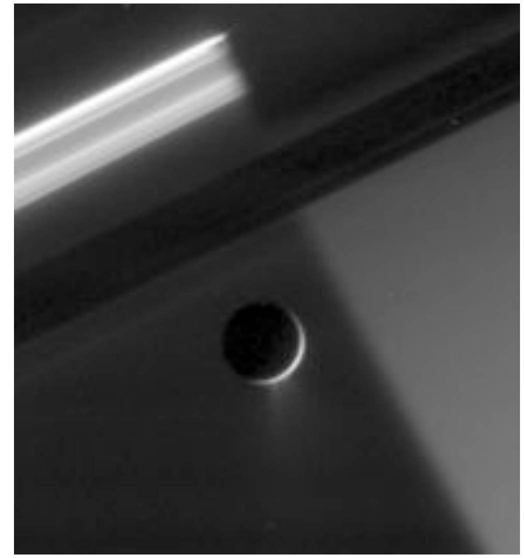
Sodium and nano-silica tell us that the source is a subsurface ocean, not clathrates or sublimation

Ocean water is exposed to space, raising energy balance problems

Plumbing:
How can conduits between ocean and surface avoid freezing shut?
(w/ Allan Rubin, Princeton U.)

Turbulent dissipation within tiger stripes may explain the phase curve of Enceladus' eruptions, and has cool tectonic implications.

Summary.



ENERGY SOURCE

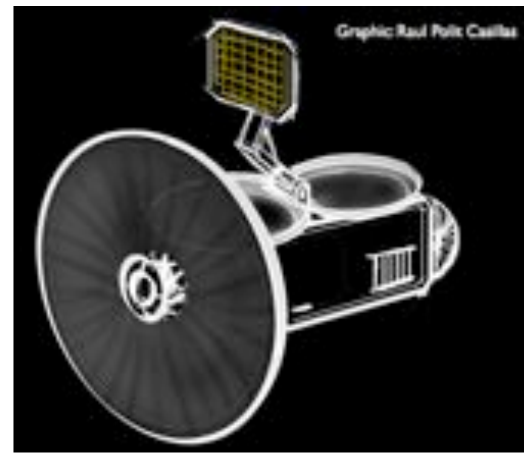
What powers Enceladus volcanism?

Tidal heating is the only plausible candidate, although the location of heating is poorly constrained.

WATER SOURCE

What is the water source for Enceladus' eruptions?

Sodium and nano-silica require a subsurface ocean source - not clathrates or sublimation.



CONNECTION

How can conduits between ocean and surface avoid freezing shut?

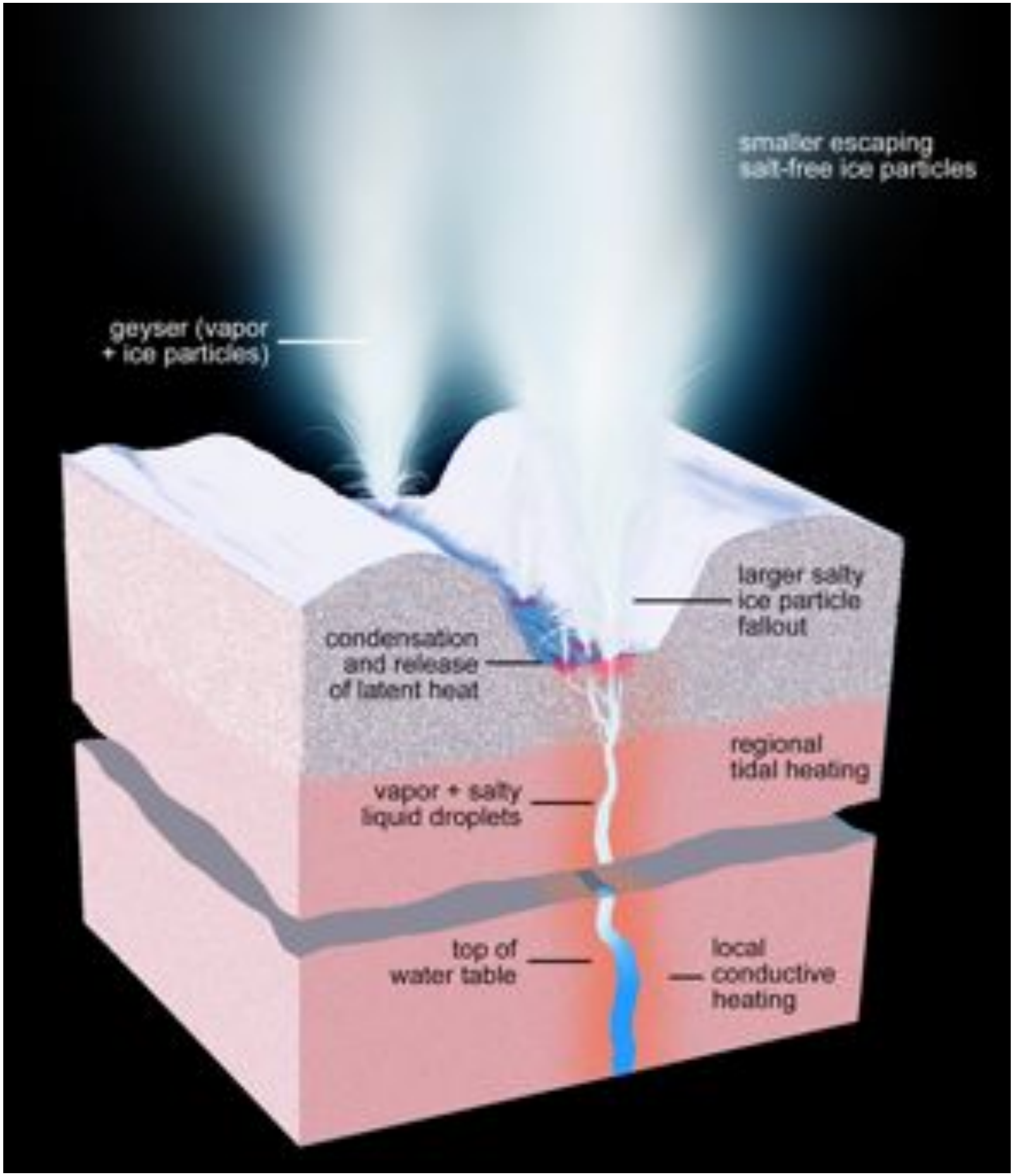
Turbulent dissipation may explain Enceladus' phase curve and long-term maintenance of fissure eruptions.

Geysers are not a passive tracer of tectonics – they can drive tectonics!

Testing habitability on Enceladus (or Europa) ultimately requires access to ocean materials - easier if turbulent dissipation maintains active fissures open for $\gg$ Kyr.

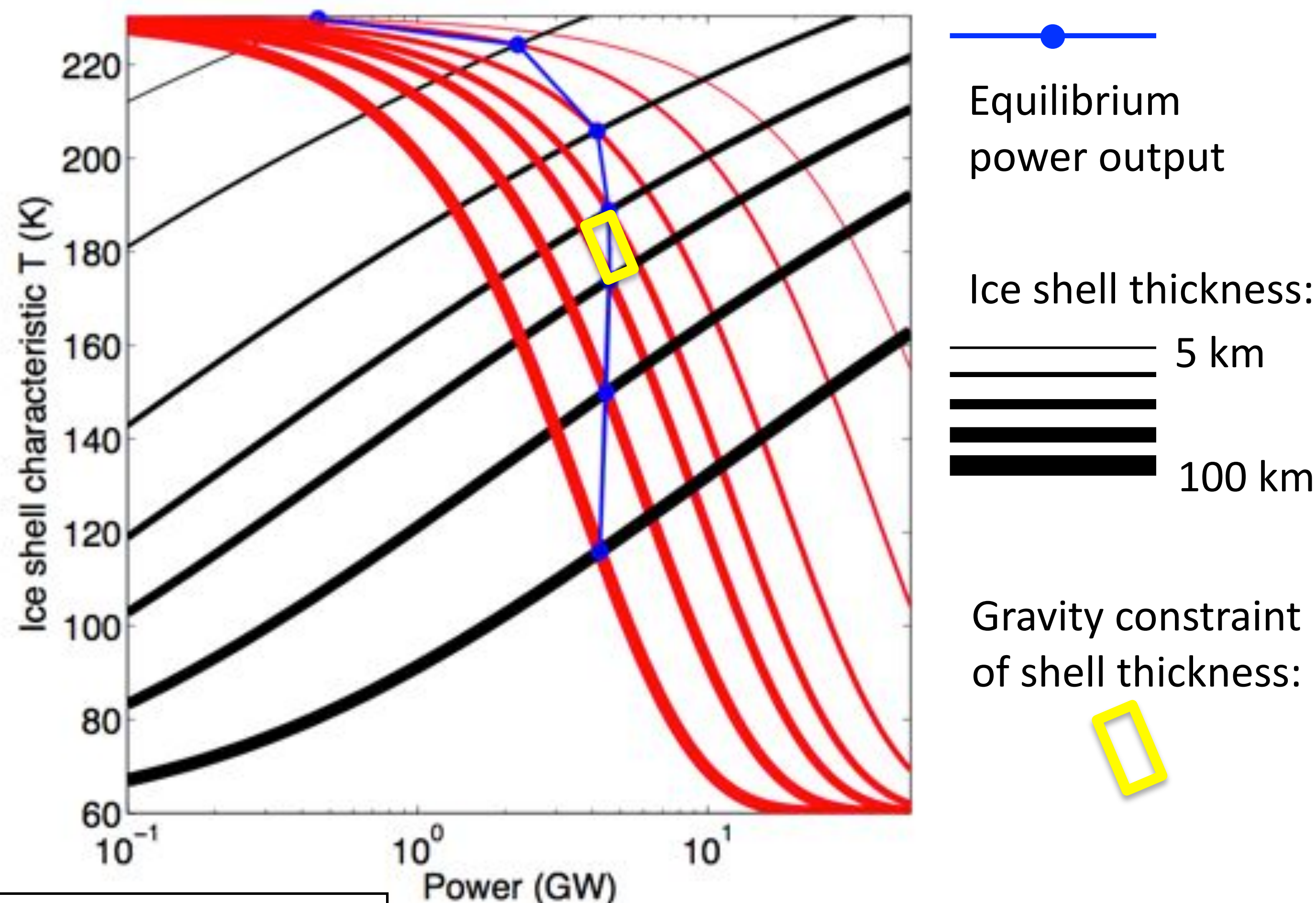
Thanks to Allan Rubin (Princeton U.) for displacement-discontinuity code and numerous discussions, & Robert Tyler, Terry Hurford, Alyssa Rhoden, & Karl Mitchell for additional discussions. **Research website: www.climatefutures.com**

Supplementary slides



Porco et al.
AJ, 2014

Tectonic feedback between subsidence and meltback buffers the South Polar terrain to 5 GW



$$\lambda = \frac{\rho_i c_p v_z Z}{k_i}$$

$$T = T_{surf} + (T_m - T_{surf})\frac{e^{\lambda\xi} - 1}{e^{\lambda} - 1}$$

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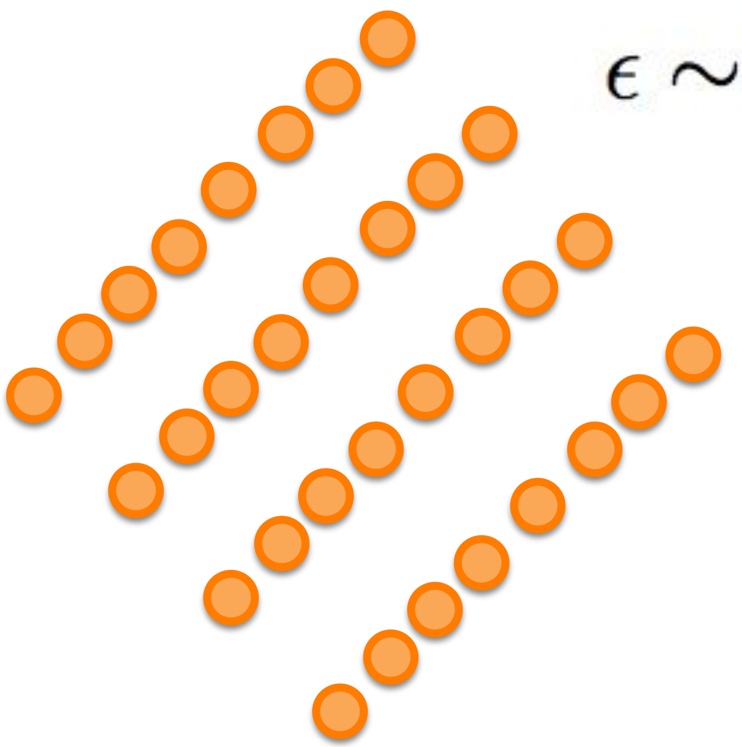
Turbulent dissipation within tiger stripes can power and (sustain the phase curve of) Enceladus' eruptions, and has cool tectonic implications!

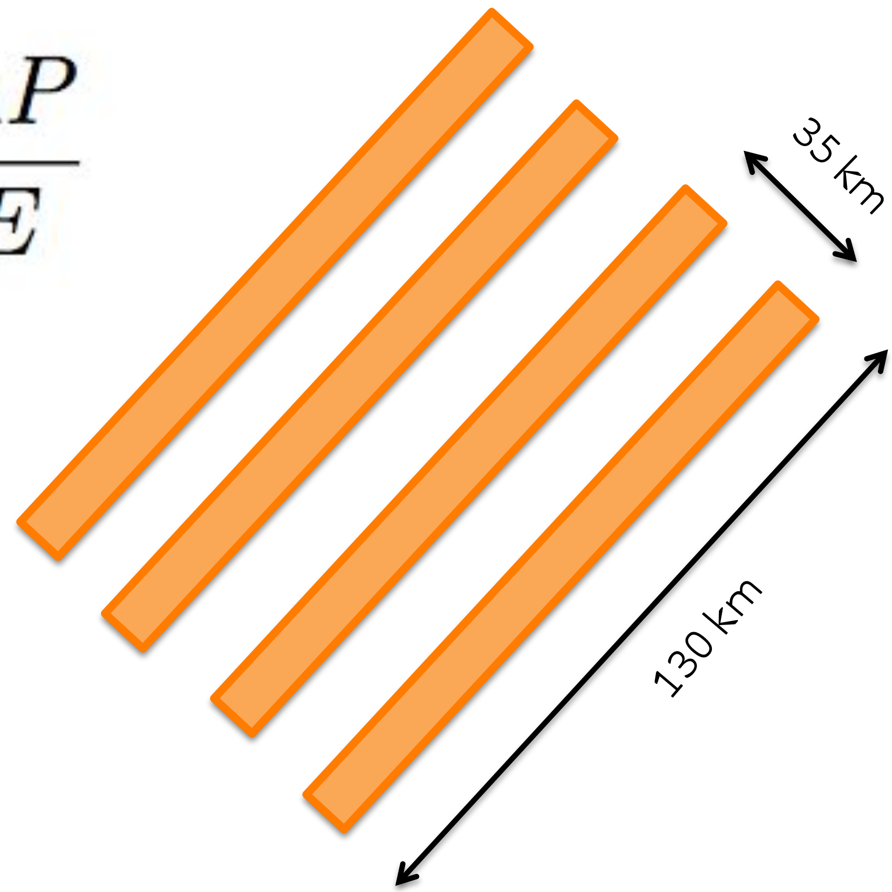
Pipe model and slot model

Option: Array of unresolved pipes
Area changes by 10^-4



$$\epsilon \sim \frac{\Delta P}{E}$$

Option: Each tiger stripe is one slot
Area changes by order unity under 1-bar pressure cycle



Apertures < 10 m (not to scale)

Testable predictions

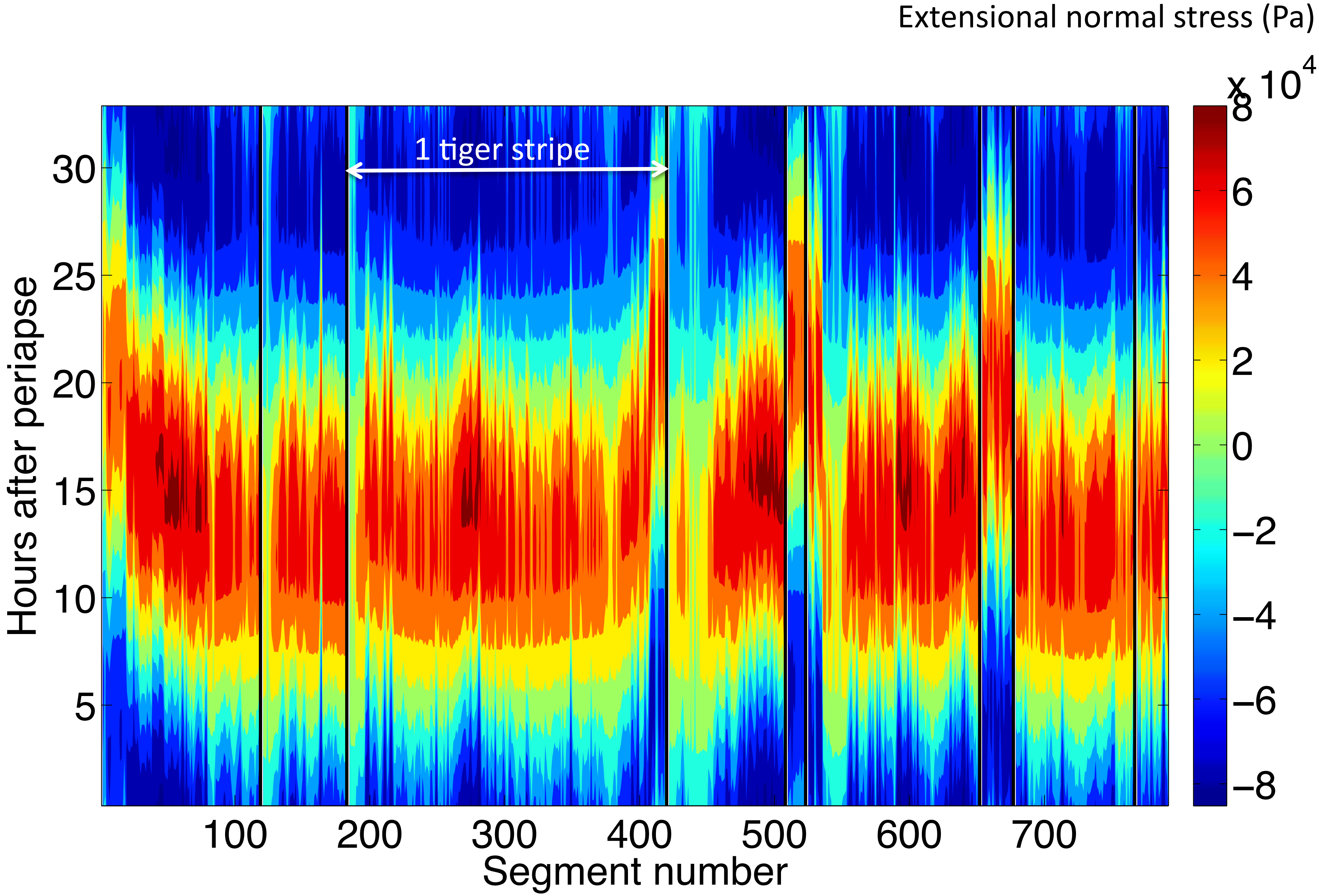
Kite & Rubin, accepted by PNAS.

For the data from Cassini's final flybys:

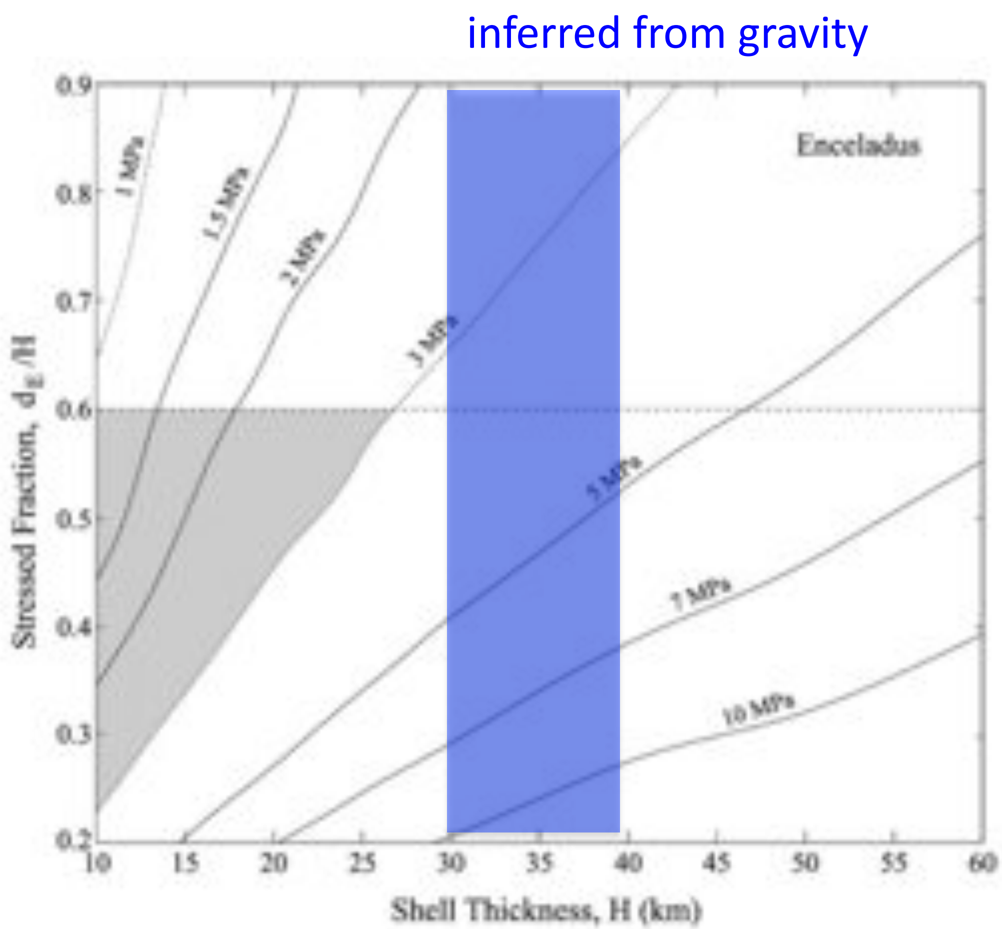
1. Endogenic thermal emission should be absent between tiger stripes.
2. No correlation between emission and *local* tiger-stripe orientation
   - Distinguishes the slot model from all crack models.
3. Smooth distribution of thermal emission
   - Contrast with spotty emission near jets (expected if flow is concentrated in pipes).
4. Steady pattern of spatial variability, in contrast to bursty hypotheses. Vapor flux should covary with ice-grain flux.

For numerical experiments:

5. Changing water level and conduit width, when coupled to gas-dynamic flow in vent (Ingersoll & Pankine, 2010; Nakamura & Ingersoll, 2012), should match phase-curve amplitude.
6. "Ropy terrain" between tiger stripes (Barr & Pruess, 2010) should be consistent with compression of condensates; topography should not bulge up between tiger stripes.

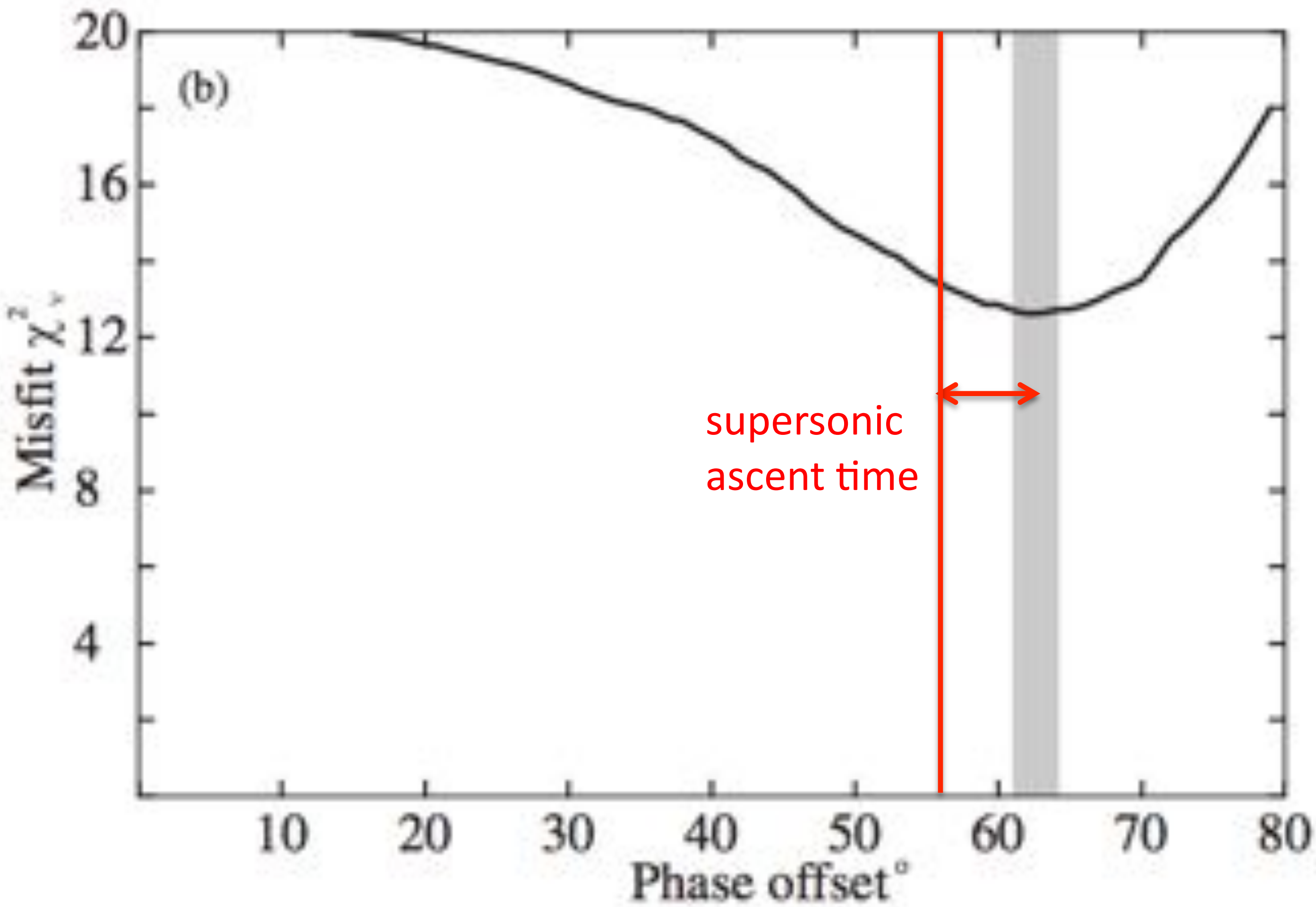


Extensional normal stress (Pa)
x 10^4
8
6
4
2
0
−2
−4
−6
−8
1 tiger stripe
Hours after periapse
30
25
20
15
10
5
100
200
300
400
500
600
700
Segment number



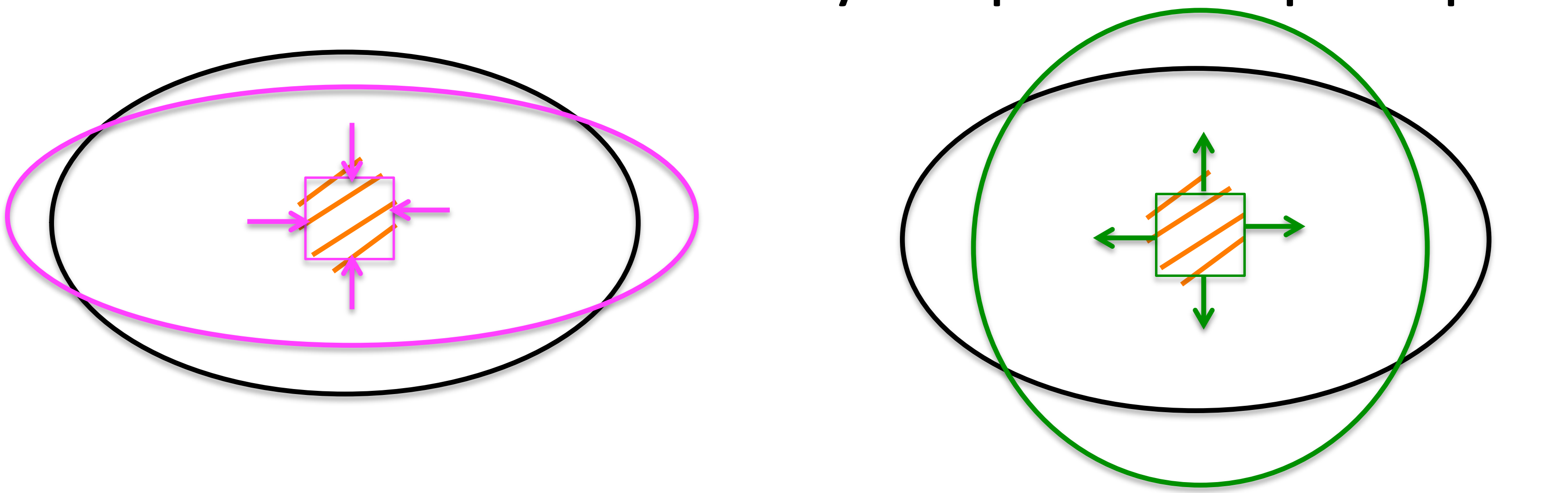
Rudolph & Manga, Icarus 2009

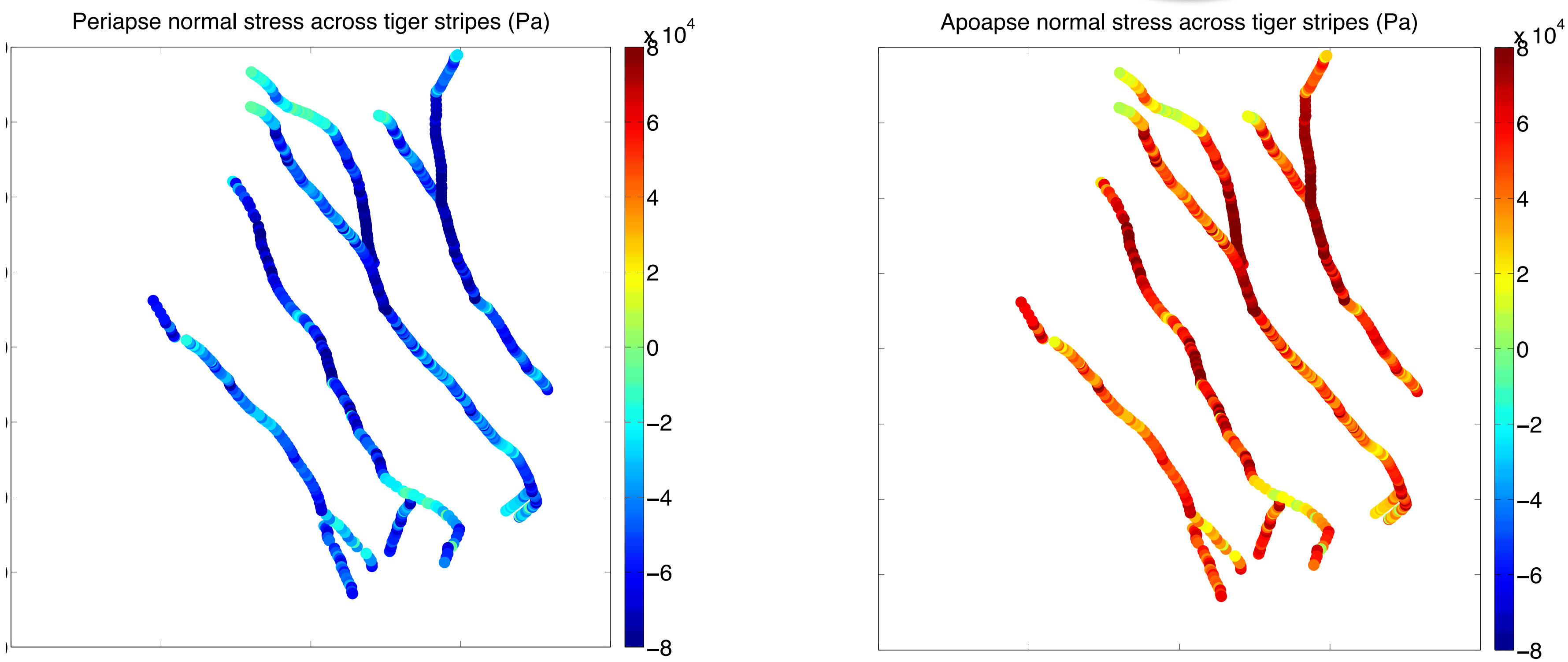
Models of tidal modulation



Nimmo et al., Astron. J. 2014

Crack models are falsified by eruptions at periapse

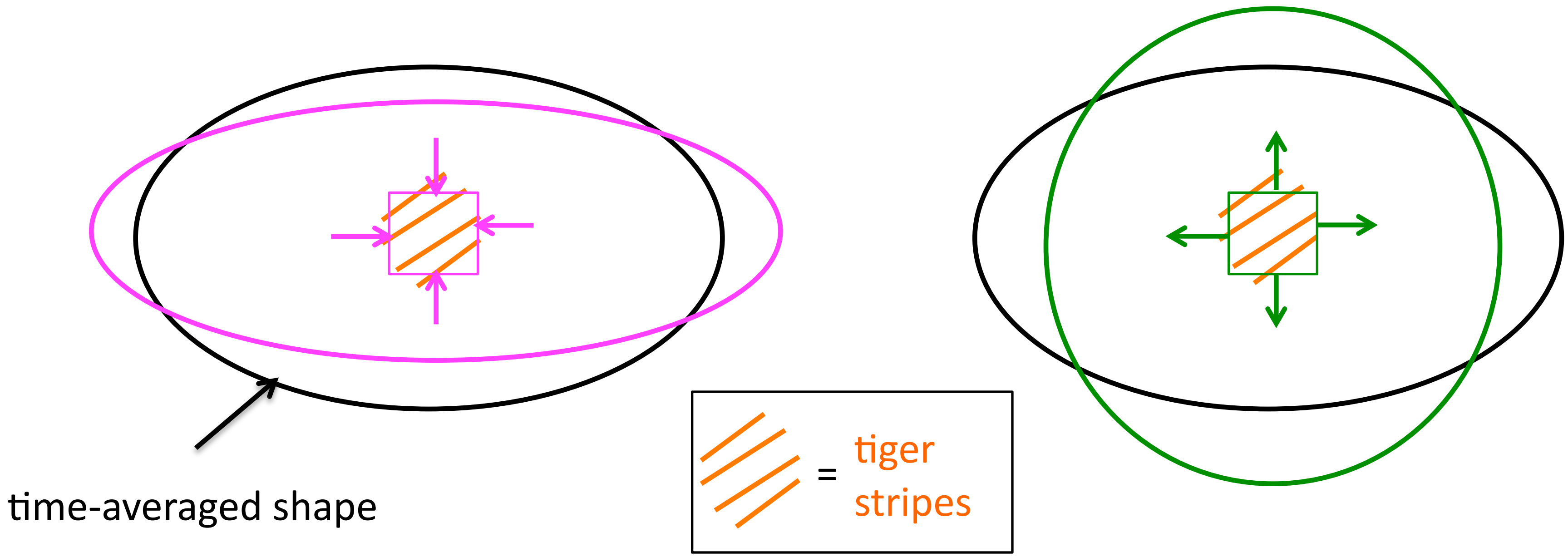




Crack models are hard to reconcile with curtain eruptions at periapse

Closest distance to Saturn
Looking down on South Pole

Furthest distance from Saturn
Looking down on South Pole



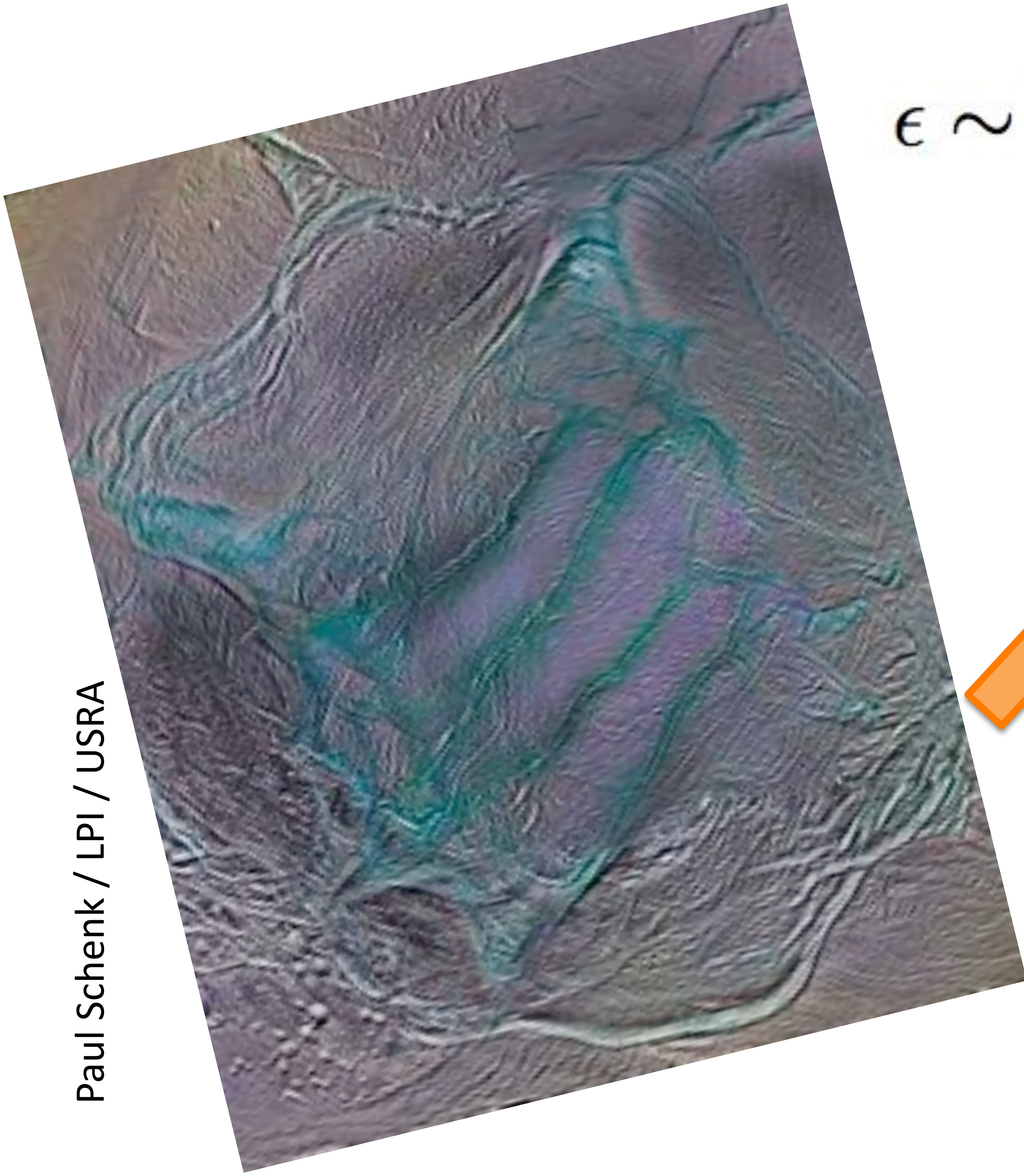
Enceladus period = 1.3 days
Enceladus orbital eccentricity = 0.0047
Tidal stress amplitude ~ 1 bar

eccentricity tide only
thin-shell approximation
k_2 appropriate
for global ocean

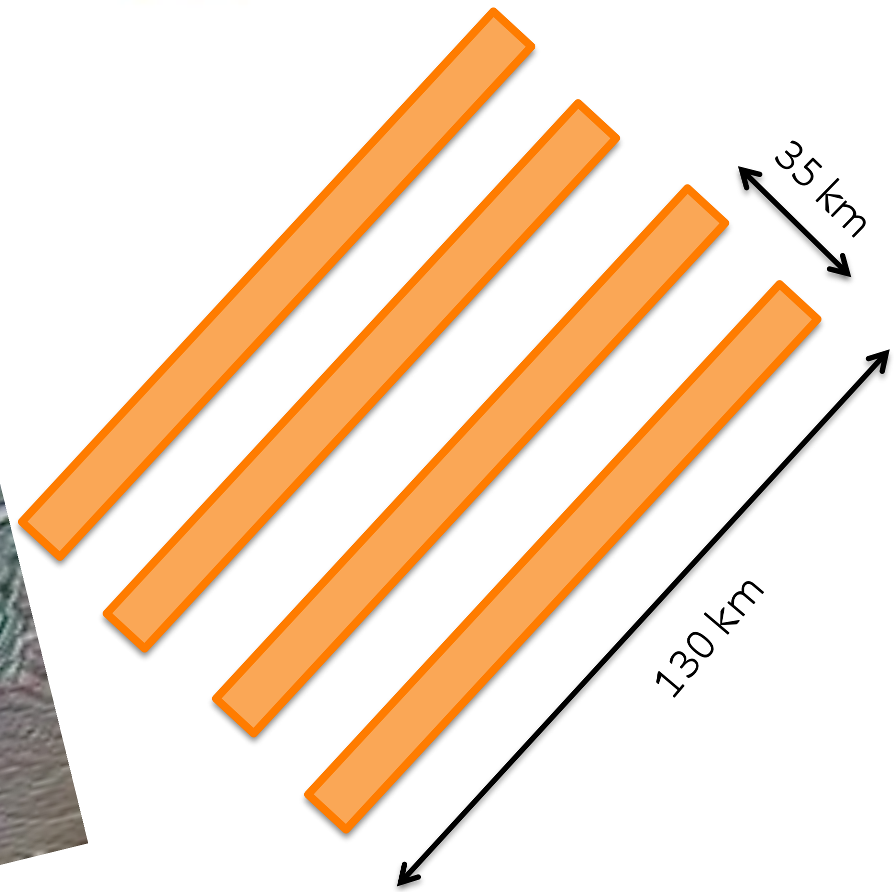
Kite & Rubin, in prep.

$$\epsilon \sim \frac{\Delta P}{E}$$

Slots interact elastically: used displacement-discontinuity method

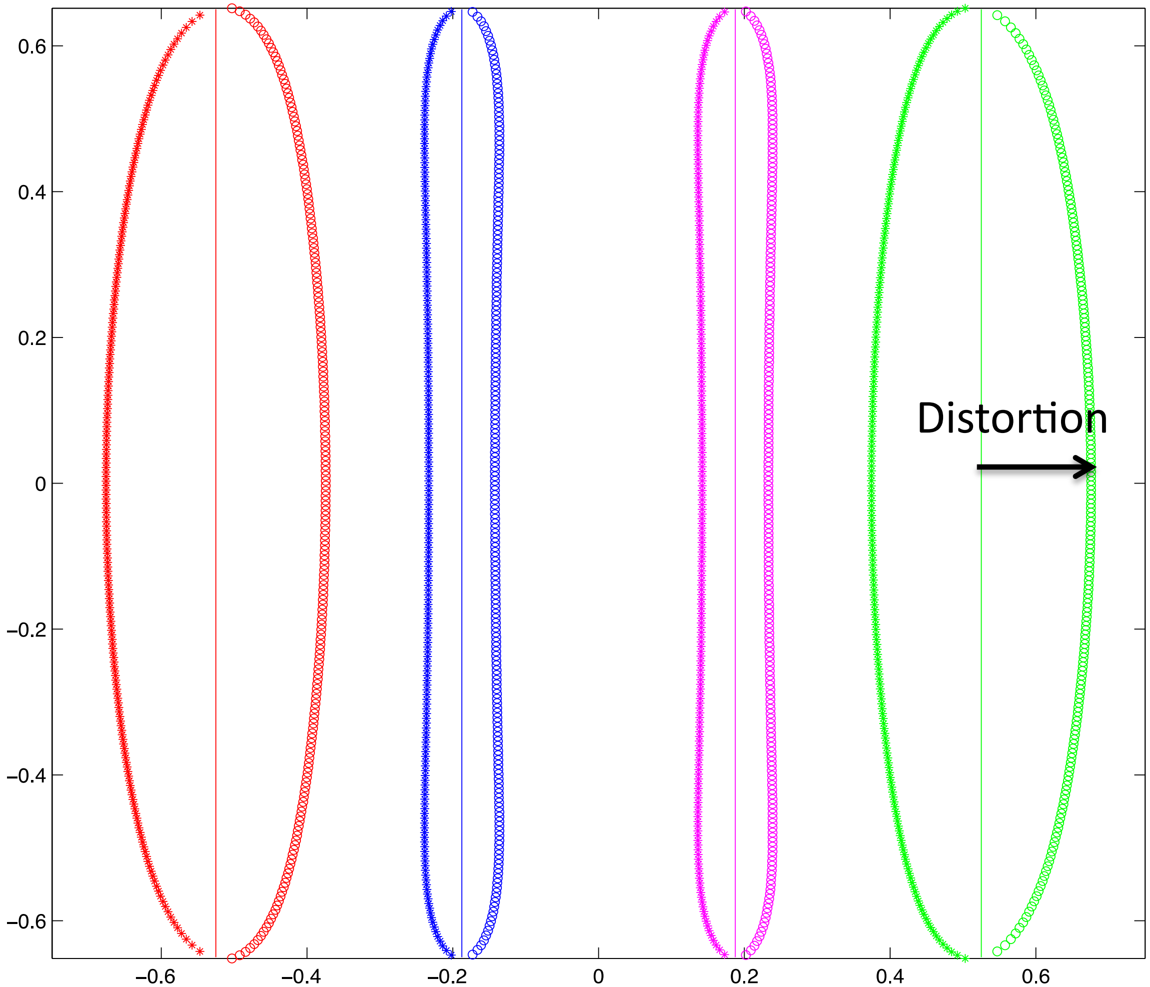


Paul Schenk / LPI / USRA



Crouch & Starfield, 1983
Rubin & Pollard, 1988

Slot-slot interactions reduce total power output



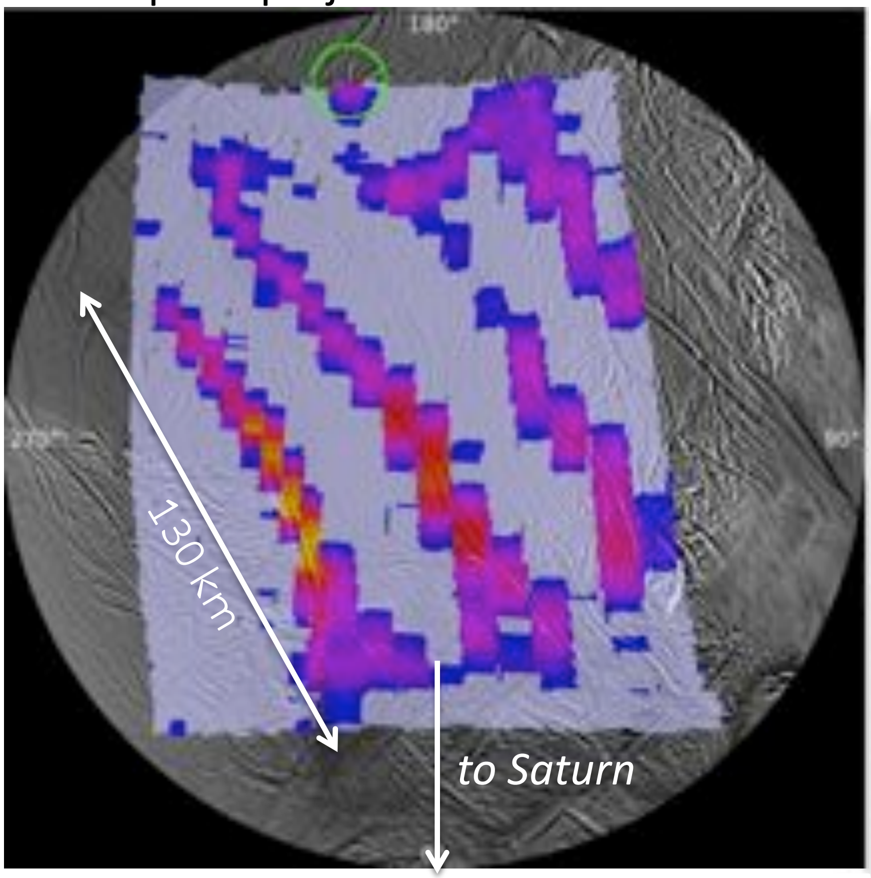
Distortion (not to scale) of idealized straight, parallel slots

Displacement-discontinuity code by Allan Rubin

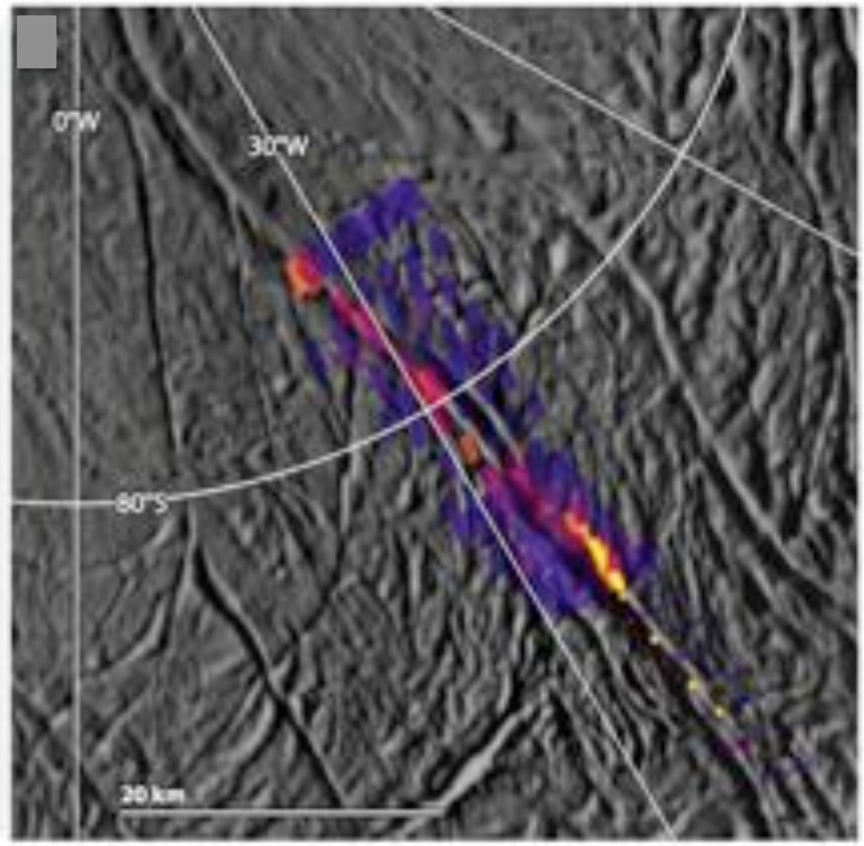
(4.4±0.2) GW excess thermal emission from surface fractures

Howett et al. 2014

South polar projection



Porco et al. Astron. J. 2014
Abramov & Spencer 2009

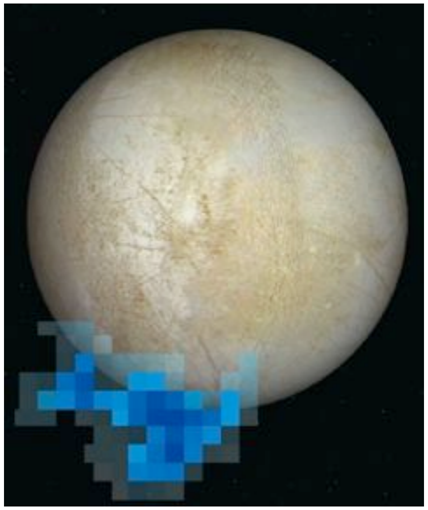


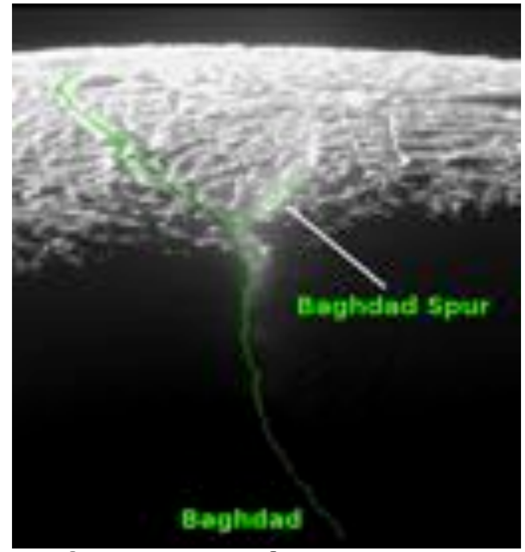
Spencer & Nimmo AREPS 2013
Spitale et al., accepted

Hotspots up to 200K
No liquid water at surface
Latent heat represented by plumes < 1 GW

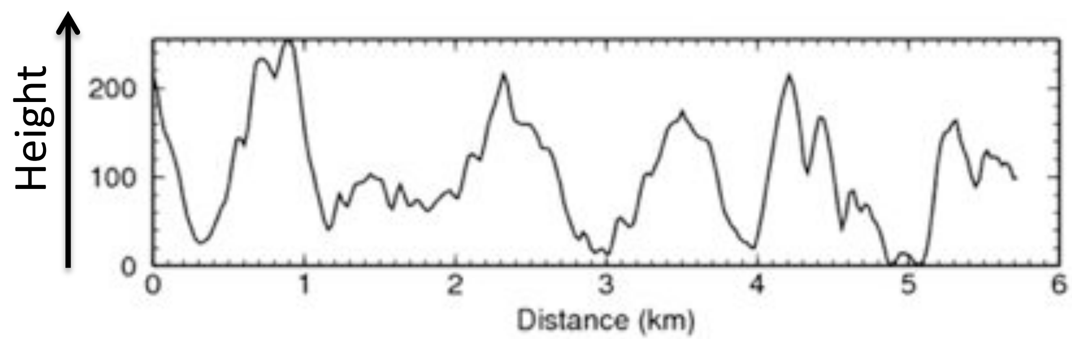
Future directions

Application to Europa
(claimed to have erupted in December 2012)





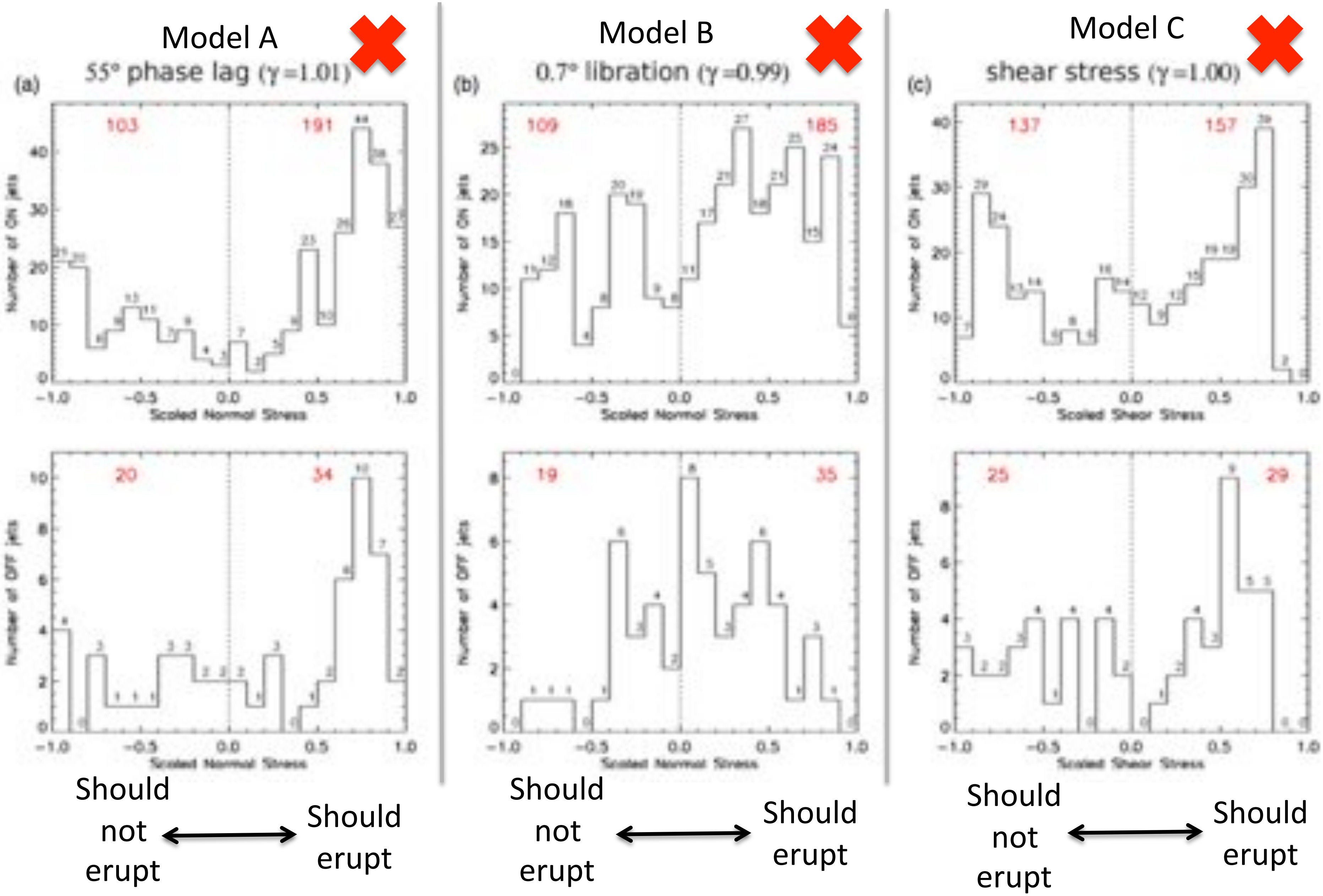
How does along-crack branching affect power?



How does changing water level and conduit width affect flow in vent?

What testable consequences would long-lived tiger stripes have for surface tectonics?

All existing models fail!

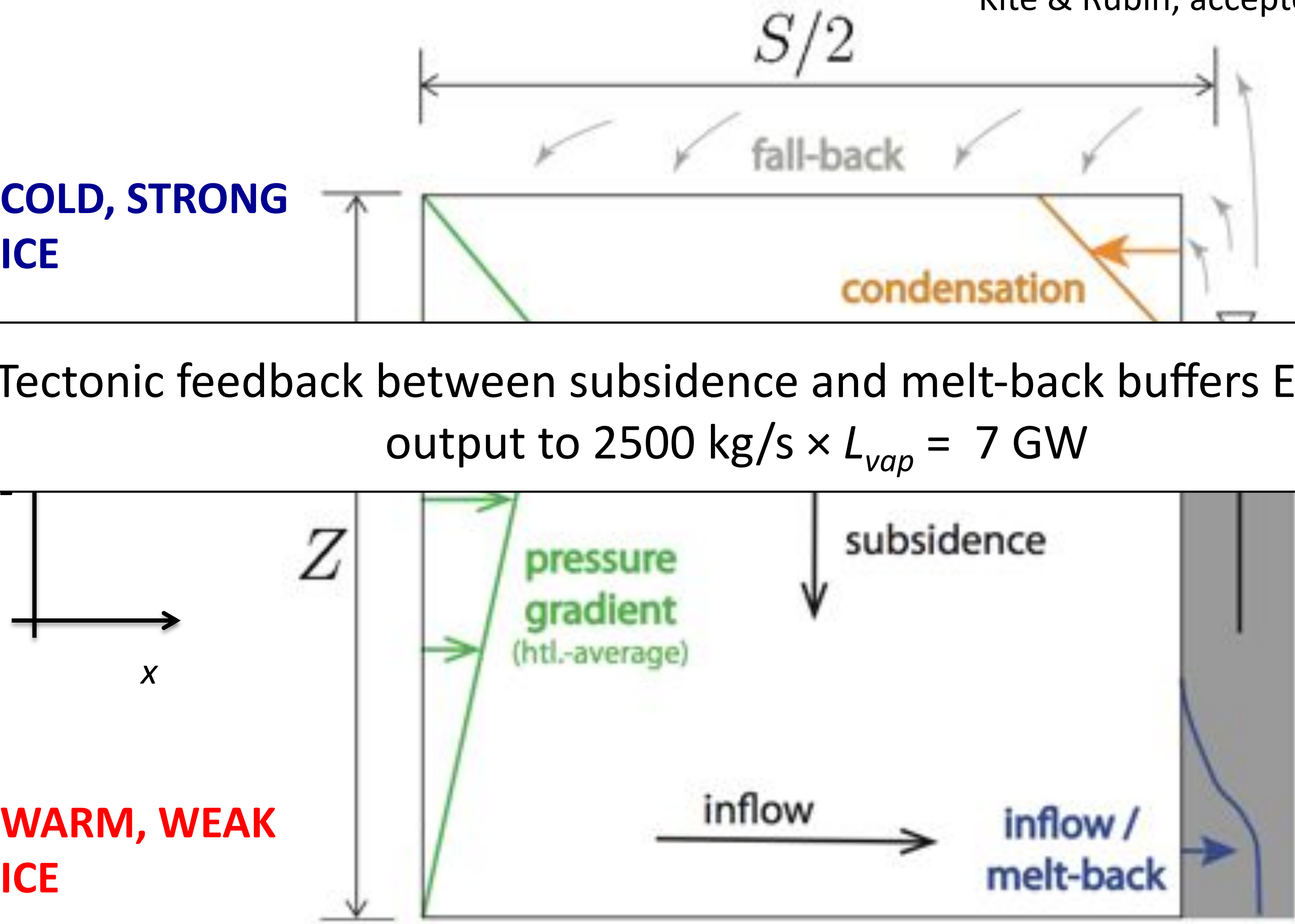


Porco et al. Astron. J. 2014

Long-lived water-filled slots have tectonic consequences

Kite & Rubin, accepted by PNAS.

COLD, STRONG ICE

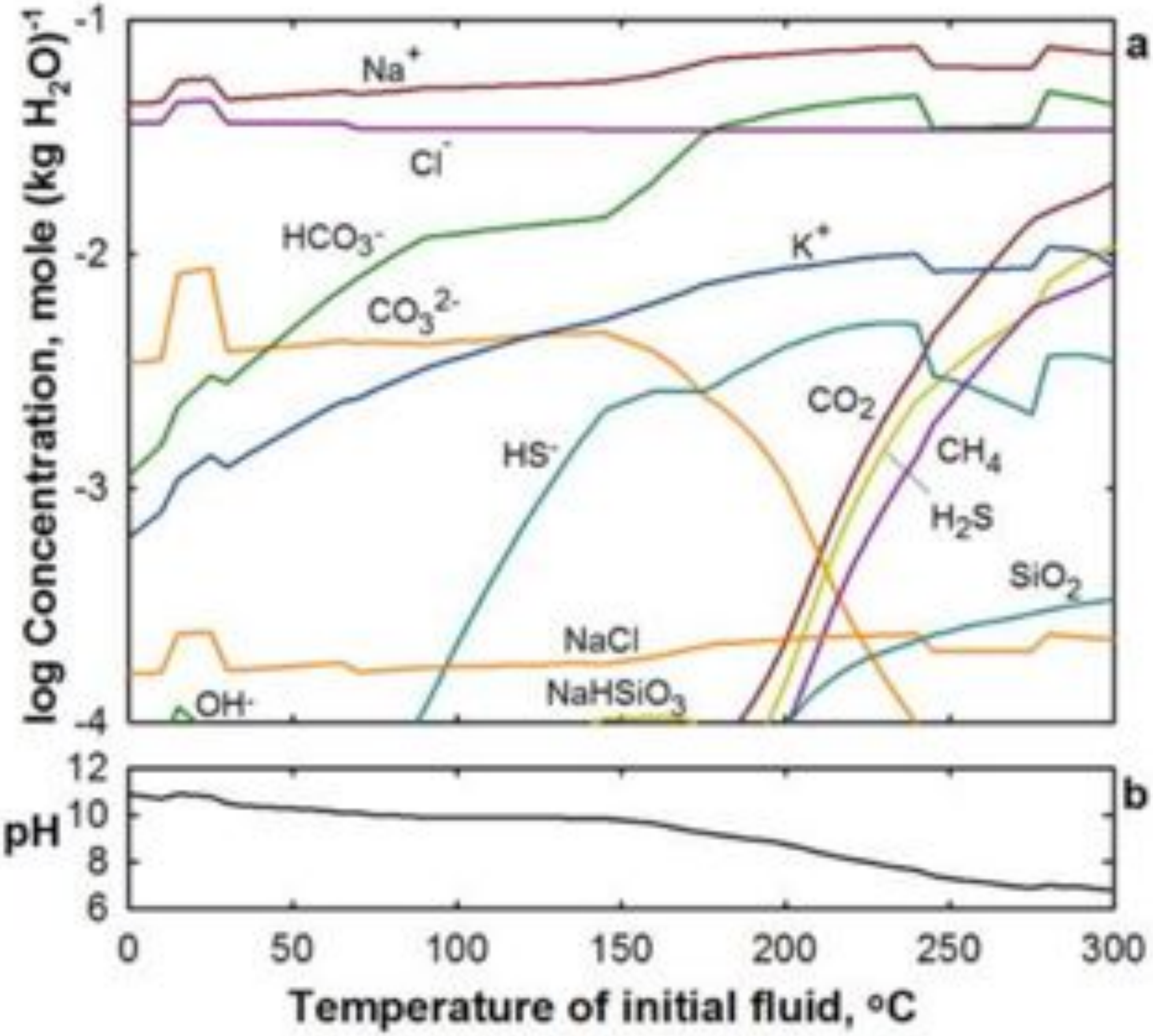


WARM, WEAK ICE

Tectonic feedback between subsidence and melt-back buffers Enceladus output to 2500 kg/s × L_{vap} = 7 GW

Salt composition matches expectations for hydrothermal leaching

Age of interaction unconstrained



Zolotov, GRL 2007